<u>MODELING OF MASS CASUALTY MANAGEMENT DURING A RADIOLOGICAL OR NUCLEAR EVENT</u>

by

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LIST OF ABREVIATIONS

ABM	agent-based modeling
ARS	Acute Radiation Syndrome
ASPR	Assistant Secretary for Preparedness and Response
BARDA	Biomedical and Advanced Research and Development Authority
CBRN	chemical biological radiological nuclear
CDC	Centers for Disease Control and Prevention
CONOP	concepts of operation
DOD	Department of Defense
DSS	decision support systems
DOE	Department of Energy
DHS	Department of Homeland Security
EAST	Exposure and Symptom Triage
FDA	Food and Drug Administration
FEMA	Federal Emergency Management Agency

GIS	geographical information systems
HHS	Department of Health and Human Services
IND	improvised nuclear device
MASS	Move, Assess, Sort, Send
NACCHO	National Association of County and City Health Officials
NARR	National Alliance for Radiation Readiness
NIAID	National Institute of Allergy and Infectious Diseases
NNSA	National Nuclear Security Agency
PAG	protective action guidelines
PPE	personal protective equipment
Rad/Nuc	radiological or nuclear event
RDD	radiation dispersal device
REAC/TS	Radiation Emergency Assistance Center/Training Site
RED	radiation exposure device
REMM	Radiation Emergency Medical Management
RITN	Radiation Injury Treatment Network
ROSS	Radiological Operations Support Specialist

SALT	Sort, Assess, Lifesaving Interventions, Treatment/Transport
SME	radiation subject matter expert
SNS	Strategic National Stockpile
START	Simple Triage and Rapid Treatment
WTW	willingness to work

ABSTRACT

MODELING OF MASS CASUALTY MANAGEMENT DURING A RADIOLOGICAL OR NUCLEAR EVENT

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Since the events of 9/11, a concerted interagency effort has been undertaken to create comprehensive emergency planning and preparedness strategies for management of a radiological or nuclear event in the U.S. These planning guides include protective action guidelines, medical countermeasure recommendations, and systems for diagnosing and triaging radiation injury. Yet, key areas such as perception of risk from radiation exposure by first responders have not been addressed. In this study, we identify the need to model and develop new strategies for medical management of large scale population exposures to radiation, review recent findings on the willingness to work (WTW) of first responders and other personnel involved in mass casualty medical management during a radiological or nuclear event, and examine the phenomena of radiation dread and its role in emergency response using an agent-based modeling (ABM) approach. Using ABM, we developed a series of models examining factors

affecting first responders' WTW during a radiological or nuclear event in the context of entering areas where radioactive contamination is present or in triage of individuals potentially contaminated with radioactive materials. In these models, the presence of radiation subject matter experts (SME) in the field was found to increase WTW. Degree of communication was found to be a dynamic variable with either positive or negative effects on WTW dependent on the initial WTW demographics of the test population. Our findings illustrate that radiation dread is a significant confounder for emergency response to radiological or nuclear events and that increasing the presence of radiation SME in the field and communication amongst first responders when such radiation SME are present, will help mitigate the effect of radiation dread and improve first responder WTW during future radiological or nuclear events.

CHAPTER 1– INTRODUCTION

Mass casualty management is a key element of emergency response for any naturally occurring disaster. For man-made disasters such as a terrorist attack, mass casualty management assumes an even greater role as these scenarios generally engender higher rates of casualties. If the event includes a chemical, biological, radiological or nuclear agent (CBRN), the level of complexity subsequently increases as conventional injuries may occur in the context of additional hazard-specific exposures. The threat of radiation exposure is a continuing concern for public health security regarding potential future terrorist acts or accidents involving radioactive materials. Such events may involve radiation exposure devices (RED), radiation dispersal devices (RDD), improvised nuclear devices (IND) or accidents involving nuclear reactors, spent fuel, or orphan radioactive sources. In each of these settings, there is the potential for radiation exposure to a large population either from internal radionuclide incorporation (the biological uptake of radionuclide internally), external radionuclide contamination, or from external radiation exposure (1).

Over the last decade, significant strides have been made to improve the nation's preparedness for managing a mass casualty radiological or nuclear event. As directed by presidential mandate and legislation, comprehensive federal guidelines for emergency planning and preparedness have been developed at the interagency level, new medical countermeasures have been approved by the FDA for radiation injury, and new radiation specific biodosimetry diagnostics are in late stage development and expected to be added to the Strategic National Stockpile (2). Though great progress has been made to modernize homeland security specifically for a radiological or nuclear event, key gaps in this field remain.

1.1 Problem Statement

"The phenomena of 'radiation dread' or 'willingness to work' within first responders and other emergency personnel groups has not been adequately addressed in emergency planning and preparedness guides for radiological or nuclear events."

Emergency response to any type of disaster is exceedingly complex due to scarce local resources, infrastructure damage and large numbers of affected population. For a radiological or nuclear event this complexity of emergency response is exponentially increased due to the added element of risk from radiation exposure, radiation injury, and environmental contamination. Notably, the impact of the phenomena of "radiation dread," i.e., extreme fear of radiation exposure has not been considered in planning guidelines. Radiation dread can be expected to adversely impact “willingness to work” of first responders, medical professionals, support staff and volunteers who would support all phases of emergency response. This would be particularly pronounced in mass casualty medical management where direct contact with contaminated individuals would be required. Recent surveys of first responders and other medical personnel have demonstrated that willingness to work for events involving radiological risks are a concern (3-6). Given this context, the role of radiation health professionals as subject matter experts and the impact that information availability plays for emergency response in this type of event is greatly increased. Yet, relatively little has been done to develop strategies for how to best integrate radiation subject matter experts into emergency response, or how the quality of information for situational awareness impacts operations during a nuclear event.

1.2 Research Questions

Key Research Questions:

- How are perceptions of risk for radiation exposure in an emergency response setting influenced by collective group dynamics?
- How does information availability affect collective perceptions of risk of radiation exposure in first responder groups?

- How are perceptions of risk for radiation exposure in an emergency response setting influenced by the physical presence of subject matter experts (SME)?
- How does willingness to triage in settings with radiation contamination change with access to subject matter experts?

1.3 Research Approach

A computational modeling approach was used to examine the effect of radiation dread on first responders' willingness to work during a radiological or nuclear event, and two different computational modeling scenarios were explored. One utilized an environment where first responders are asked to enter an area with radioactive contamination for search and rescue. The other scenario includes a triage environment where first responders provide medical treatment to civilians potentially contaminated with radioactive contamination. The role of communication, presence of radiation SME and degree of willingness to accept radiation exposure and its subsequent effect on social group interactions was examined.

1.4 Overview of Nuclear and Radiological Terrorism

The probability of future acts of nuclear terrorism is the subject of much debate. Scholars such as Graham Allison and others, believe nuclear terrorism to be a real threat to national security, citing the existence of ongoing weapons trade within international black markets for either the illicit sale of a nuclear weapon or for the equipment necessary to enrich uranium, or the fissile material itself, potentially allowing non-state actors to construct their own improvised nuclear device (7-10). Others like Michael Levi and John Mueller believe nuclear terrorism to be unlikely citing the technical, operational and financial barriers independent groups would face in trying to acquire, construct or transport a nuclear device (11, 12).

The threat assessment probability of radiological terrorism enjoys a much more cohesive consensus consisting of widespread agreement that radiological terrorism is entirely feasible and might happen at any time (13-16). This is both due to the potential ease of acquisition of radioactive materials and the varied possible methods of action including both radiation exposure devices (RED), and different types of radiation dispersal devices (RDD). Powerful radioactive sources are used throughout commercial industry and medicine and represent a wide distribution of potential sources for theft. Radioactive sources also go missing every year, both in the U.S. and worldwide and sealed radioactive source incidents resulting in human injury from these lost industrial or medical radioactive sources surprisingly happen with relative frequency (17-20). Historical examples of use of radiological terrorism are rare, but include the case of Chechen rebels who placed, but did not detonate, a dirty bomb containing cesium-137 in a Moscow park in 1995, and of a British citizen who was arrested for attempting to build a dirty bomb out of americium-241 taken from smoke detectors (16, 20). There have also been reports of al-Qaeda extremists attempts to obtain strontium-90 a powerful radioactive source (20, 21).

There is also diversity found in the type of possible radiological terrorism. A RED consists of a radioactive source which might be placed in virtually any location to emit harmful ionizing radiation exposures to persons who come in close proximity. A passive RDD consists of a method or device to disperse radioactive material in a non-explosive manner, which may then be ingested, inhaled or deposited on the skin. A kinetic RDD consists of a conventional explosive device combined with radioactive material which would then cause both dispersal of radioactive contamination and traditional blast injuries or a “dirty bomb.”

Though an RDD or RED may be constructed and deployed with relative ease, it is unlikely that the scale of injury from radiation exposure would cause mass fatalities (15). This is due to the challenges of construction and transportation of such a device. In order to build an RDD capable of causing mass radiation casualties, the terrorists themselves would suffer severe health effects from being in proximity to the source itself (22, 23). Addition of shielding sufficient to protect the operator is unfeasible in a practical sense and would also inhibit detonation/dispersal of the radioactive material. The societal impact however, from release of a low grade radioactive material would cause widespread panic, economic disruption and render a large geographic area unusable for a long period of time. In contrast, a RED could cause severe or mortal radiation injury to individuals who were in close proximity for a significant amount of time, but this would not occur on a mass scale and would not cause physical contamination of an area. Though nuclear power plant attacks are not explicitly included in nuclear or radiological terrorism paradigms, explosive attacks on nuclear power plant reactors would result in essentially a massive RDD and the possibility of such attacks are the subject of continuing national security concerns (14, 23, 24)

Significant disruption of society would occur in all of these scenarios with a high level of involvement of first responders and the medical community to manage the affected civilian population. Though questions regarding the likelihood of future nuclear or radiological terrorism incidents remain, there is certainty in the need for national readiness and comprehensive emergency planning and preparedness guidelines for management of such events.

1.5 Contribution of the Research

Computational modeling of these scenarios can be used to develop policies to mitigate perceived risk of radiation exposure for first responders involved in mass casualty management of radiological or nuclear events and develop strategies to leverage the role of communication and presence of SME to diminish the influence of radiation dread. Emergency response for radiological and nuclear event scenarios is uniquely challenging due to its highly complex, low familiarity, low probability and highly dreaded nature. Additional research in this area will fill an unmet need for improved disaster management strategies for mass casualty management of events involving radiation injury and radiation exposure to potentially save human lives.

CHAPTER 2 – LITERATURE REVIEW

Mass Casualty Medical Management During a Nuclear Event: A Literature Review of Key Concepts

This review will examine key elements of mass casualty medical management for radiological and nuclear events, the role of computational modeling in development of emergency planning and preparedness for mass casualty events, the history and psychological phenomena of radiation dread, and existing data on the influence of radiation dread on first responders' willingness to respond to a radiological or nuclear event.

2.1 Mass Casualty Computational Modeling

Medical management is an integral part of emergency response and critical to large scale disaster response. Recent advances in data science have enabled use of computational social science methodologies for research studies in disaster response and the emergence of a new field of computational social science of disasters (25). Though computational modeling has become an accepted tool for modeling comprehensive disaster response, application of computational modeling for mass casualty response is still relatively novel. Mass casualty management, both in the pre-hospital and hospital setting includes transport and triage of the injured, resource allocation with emphasis on scarce resource allocation of medical countermeasures, management of physician/staff and patient admission resources and communication. A recent literature review on mass casualty modeling found no existing consensus on criteria for distribution of casualties in trauma related settings (26). Models of healthcare response in a disaster differ from other types of models as they are designed to support continuing planning efforts to improve emergency response and may be used for pre-event strategic planning or to support operational decision made during an event (27, 28).

Computational modeling of key aspects of mass casualty management can be segregated into agent-based models and other model types including discrete event modeling and various types of simulations. These studies are contrasted by a preponderance of non-computational methodologies in mass casualty management research including use of surveys, table-top and live planning exercises, Delphi studies, and analyses of specific case studies (26, 29-33). The benefit of using a computational social science approach for modeling specific aspects of emergency response lies in the ability to model complex social interactions. As disasters are fundamentally examples of complex dynamic systems with independent agents interacting on a myriad of levels guided by a non-uniform set of priorities, the use of computational modeling to test or develop theories regarding disaster response has the capacity to be a powerful tool in advancing disaster response efficacy.

Agent-based modeling (ABM) is particularly suited for simulating emergency response and crisis management in this context given its fundamental capacity for simulating the behavior of complex systems. Agent-based simulation is an accepted platform for modeling human behavior and movement under realistic environmental conditions. Through use of “agents” or individuals this computational methodology allows independent agent interactions both between the agents themselves and the simulated environment (34). Different agent groups can be assigned alternative sets of rules to guide decision making processes and model heterogeneity of response in a group setting influenced by the dictates of the environment. Observation of emergent behavior patterns in this context allows exploration of key factors which drive behavior in the given setting. Such models have been developed to examine emergency management in different types of crisis scenarios relative to factors such as traffic congestion, epidemiology, information management and single and multi-site disaster sites (34-36). Multi-agent modeling has also been used to examine broader concepts of disaster management including decision support systems, interaction of crisis organizations and collective decision making (37-39). A variety of agent based simulation platforms are available for modeling crisis response including DrillSim, DEFACTO, ALADDIN, RoboCup Rescue and FireGrid (40). Agent-based modeling has been particularly utilized for modeling human movement and behavior in various evacuation simulation models in urban settings (41-44).

Application of agent-based simulation for modeling mass casualty medical response has been less abundant, but new studies have used ABM to model triage, transport and medical countermeasure deployment. Smith et al. used ABM to model the complexity of mass casualty response in a simulated sarin release using a topographically accurate model environment with the help of geographic information system (GIS) technology. Their model focused on dose and surge response in the context of emergency medical services, hospital surge capacity and psychosocial victim characteristics. They found that cumulative mortality increased in a non-linear rate with relation to sarin dose and level of systemic stress and that reducing ambulance response time and increasing emergency medical responders improved mortality rates. They also noted that associated psychosocial characteristics of excessive worry and low patient compliance added complexity to the response and increased demands on limited health care resources (45). Guclu et al. used the ABM platform HAZEL to simulate realistic synthetic populations based on US Census data to model evacuation behavior and access to primary health following a natural disaster. They identified areas with high deficits in primary care access and found that improving providers capacity had less impact of availability of care than strategic placement of providers in areas with the most populous census tracts. These findings demonstrate the utility of computational modeling to inform health care planning for responders in disaster affected areas (46).

Carley et al. used a multi-agent simulation platform BioWar to run scalable simulations of population level health care seeking behavior, patterns of work and school absenteeism and pharmaceutical demands following a biological weapons attack (47). Other studies have used ABM to simulate mass casualty scenarios to improve response planning and include GIS supported simulations which model processing capacity of casualties through the availability and location of emergency medical responders, ambulances, hospitals the individual hospital capacity (48, 49). Bae et al. also utilized GIS in support of a comprehensive agent-based model which simulated many aspects of mass casualty management including triage, transport and hospital care from both the pre-event, pre-hospital and hospital settings (50).

ABM has also been used to model specific aspects of mass casualty response including pre-hospital triage. Hawe et al. using the ABM platform STORMI found that rates of triage misclassifications directly correlated with resource levels and that scarce resource allocation between multiple incident sites should be driven by the distribution of casualties between sites (51, 52). Distribution of scarce resources in mass casualty events remains a key aspect of response planning. Gabdulkhakova et al. have used an agent based system to model and develop an algorithm to aide operation managers of mass casualty incidents with decision making processes for resource allocation (53). Several studies have also developed multi-agent models to simulate the interactions of autonomous agent groups to improve care of patients in emergency departments including Laskowski and Mukhi which used ABM to improve triage management of large numbers of patients in the emergency room setting and policies of ambulance or patient redirection to other facilities to improve care (54-57). Ambulance transport of injured in mass casualty scenarios is also a key aspect of disaster medical management and has been modeled using ABM supported by GIS to predict response times and the route selection behavior of drivers (58).

ABM modeling of information management during mass casualty events has been useful in examining challenges in information flow which affect patient care at the logistical and organizational levels. Narzisi et al. used ABM to generate a heterogeneous population of agents and model hospital topology and the phenomena of over-triage, or patients with non-life threatening injuries overwhelming the hospitals closest to the event site. They found that emergency managers could improve mass casualty management outcomes through improved communication to guide patient movement and redistribute patients amongst hospital networks (59). Zhu et al. used the multi-agent platform R-CAST-MED to explore information challenges particular to mass casualties, how information was shared between agents and the effects of decision recommendations made based on limited information. Their findings recommend the use of more efficient information sharing networks to improve coordination of care in mass casualty settings (60).

Though the application of computational social science methodologies in disaster management research is still an emerging trend, there is ample evidence that these modeling platforms are of significant value in examining complex large dynamic systems (25). Though favored methodologies such as Delphi surveys, tabletop simulations and live field exercises remain invaluable tools to simulate emergency management of mass casualties and comprehensive disaster management, computational modeling allows for more cost-effective and adaptive tools to test and develop management theories. ABM of mass casualty medical management is particularly appropriate as mass casualty events intrinsically constitute a heterogeneous agent population with competing goals and priorities. New studies which utilize multi-agent simulation should provide novel findings which will drive development of new operational protocols for disaster management and improve patient outcomes.

2.2 Mass Casualty Medical Management of Radiological/Nuclear Events

Computational modeling has not yet been widely applied to development and improvement of emergency preparedness and response planning for radiological and nuclear events. However, since the events of 9/11 a concerted interagency effort has been made at the federal level to develop consensus guidelines for emergency response to potential radiological and nuclear event scenarios. These planning documents include “Key Response Planning Factors for the Aftermath of Nuclear Terrorism,” “Planning Guidance for Response to a Nuclear Detonation,” “Nuclear/Radiological Incident Annex to the Response and Recovery Federal Interagency Operational Plans” and “Radiological Dispersal Device (RDD) Response Guidance: Planning for the First 100 Minutes” (61-64). Organizations such as the Radiation Injury Treatment Network (RITN) and National Association of County and City Health Officials (NACCHO) and the National Alliance for Radiation Readiness (NARR) have been leveraged to provide medical management support of mass casualties involving radiation exposure or guidance on emergency management specific to disasters involving radiation (65-68). New web based resources such as the Radiation Emergency Medical Management (REMM) portal managed by the U.S. Department of Health and Human Services and Centers for Disease Control and Prevention (CDC) web based resources have also been developed to aid in the management of radiation casualties (69, 70). Development of new radiation injury specific triage protocols, medical countermeasures, and biodosimetry diagnostics for radiation injury have also generated a large field of research aimed at meeting the challenges of mass casualty management for radiological and nuclear events (71).

Mass casualty triage is the first challenge for radiological and nuclear events. There is no single accepted triage system for conventional injury in the United States. Currently there are numerous triage systems in use including START (Simple Triage and Rapid Treatment), MASS (Move, Assess, Sort, Send) and SALT (Sort, Assess, Lifesaving Interventions, Treatment/Transport) (72). The SALT triage system has been proposed as national concepts of operation (CONOPs) for a uniform triage system but has not been universally adopted (73). This lack of consensus is further complicated by the need for additional triage systems adapted to meet the specific needs of events where chemical, biological, radiological or nuclear (CBRN) threat agents are present (74). Within the field of CBRN emergency management, there are two major perspectives regarding the utility of an 'all hazards' approach to emergency management. One approach is pro-all hazards and feels that adoption of a broader emergency response framework, which is capable of responding to any CBRN threat is the best methodology (75, 76). The other perspective argues that an inclusive all-hazards approach sacrifices effectiveness and that triage systems need to be tailored to the specific type of CBRN threat. For example, Cone and Koenig argue in support of an all hazards viewpoint that additional CBRN specific triage categories can be added for radiation exposures to supplement a more comprehensive triage system, but do not present an explicit methodology for ranking concurrent triage criteria for radiation injury and conventional injury (77). Coleman et al. in contrast have developed a triage model for radiological casualties called the RTR (Radiation-specific TRiage, TReatment, TRansport sites) medical response system. This conceptual triage model comprises radiation specific triage, treatment and transport for managing radiological injuries and is proposed for use within a wider SALT triage application (78, 79). Use of radiation injury specific triage cards have also been proposed for integration with conventional triage protocols and an EAST (Exposure and Symptom Triage) tool has been proposed which would link GIS position location of the patient's radiation exposure with clinical assessment data for radiation injury specific triage (80, 81).

Radiation injury mass casualty triage protocols for the hospital setting have also been developed with emphasis on the priority of basic triage i.e., conventional blast/thermal injuries management over radiation induced injury triage. Protocols for scanning patients for the presence of radioactive material and subsequent decontamination, protective action guidelines and use of personal protective equipment for hospital personnel and medical countermeasure recommendations for radiation injury have been proposed (82-85). Planning and response documents for mass casualty management of radiological or nuclear events for state and local emergency planners have also been developed in the context that most local healthcare systems have committed few resources to planning for these types of event scenarios and a general lack of diagnostic knowledge of symptoms and criteria assessment of radiation injury in general medical practitioners (86-88).

Perhaps the two greatest challenges for mass casualty triage of radiological or nuclear events are population screening to determine radiation dose received and subsequent allocation of scarce resources for radiation injury-specific medical countermeasures. Medical management of radiological scenarios is complicated by the lack of screening diagnostics for radiation exposure. In most cases, there are no outward signs that a person has been exposed. Yet, the progression of Acute Radiation Syndrome (ARS) is well characterized and if the level of dose is known, the physician can predict which symptoms will occur and the expected timeframe of their onset. Radiation biodosimetry is also needed for screening the ‘worried well’ or asymptomatic walking wounded who could overwhelm exiting triage systems, wanting to know if they have received a radiation exposure(71). The “worried well” refers to those healthy, uninjured individuals who present for medical evaluation due to concerns that they may have been exposed to a threat agent. In the case of a radiological or nuclear event, the worried well are that section of the population who are worried that they may have been exposed to radiation. Since radiation is invisible to the naked eye and ARS has nonspecific symptoms, it is impossible for civilians to know if they have received a harmful radiation exposure.

This phenomenon is well characterized and was evident during the 1987 radiation accident in Goiania, Brazil where over 125,000 people requested evaluation for radiation exposure. This population was surveyed using labor intensive techniques to scan for external and internal radiation exposure. Radiation biodosimetry diagnostics were not used, as a field deployable diagnostic was not available. Of this surveyed population, 46 received medical countermeasures specific to radiation exposure and only 14 actually developed ARS (15, 89, 90). Therefore, the most critical component to mass casualty management of radiological or nuclear event scenarios is dosimetry. Biodosimetry, or the capability to estimate unknown received radiation dose in the absence of physical dosimetry, is critical for radiation injury triage.

Currently, biodosimetry diagnostics are not used for pre-hospital mass triage screening. In the scenario of a radiological or nuclear event in a highly populated city in the United States, even greater numbers of people than the Goiania incident are expected to request screening for radiation exposure. For this reason, point-of-care (POC) field deployable and high-throughput reachback laboratory systems for radiation biodosimetry diagnostics are being developed. These technologies are currently in the late development /validation phase with the Food and Drug Administration (FDA) and the POC biodosimetry devices and materials to support sample collection for reachback biodosimetry platforms are scheduled to enter the strategic national stockpile (SNS) once they obtain final licensing (91-94). These biodosimetry diagnostics are the critical component to successful mass casualty screening of a radiological and nuclear event not only because they provide the necessary tools to triage radiation injury but as they guide scarce resource allocation of radiation specific medical countermeasures and selection of which medical countermeasures to use (17, 95-98). In the last decade, the Biomedical and Advanced Research and Development Authority (BARDA) under the Assistant Secretary for Preparedness and Response (ASPR) at the Department of Health and Human Services (HHS) and the Radiation and Nuclear Countermeasures Program at the National Institute of Allergy and Infectious Diseases (NIAID) has supported research and development into biodosimetry diagnostics and new medical countermeasures for radiation injury (2, 71, 99, 100). These diagnostics and countermeasures are designed to support existing protocols for medical management of radiation injury (101-104). Guidelines for using biodosimetry for mass casualty management of radiation injury have also been proposed but these are not yet operationalized (105-107).

Though computational modeling approaches to emergency management of natural disasters is becoming more prevalent, application of these modeling approaches to manmade disasters such as chemical, radiological or terrorist type events remains novel (27). In the context of emergency management for radiological or nuclear events there are a few select studies which use agent-based modeling simulations. Amir et al. used an ABM approach to model evacuation behaviors in the context of a nuclear reactor accident.(108) Parikh et al. used agent based simulation to model human social interactions and movement following a nuclear detonation and Chandan et al. the effect of emergency communication on these behaviors.(109, 110) Other non-ABM computational methodologies used to model emergency management specific to radiological and nuclear events include development of decision support systems (DSS) to aide coordination of emergency response and modeling of medical countermeasure distribution of potassium iodide following such an event (111-113). Use of multi-objective optimization to model protective actions to minimize risk in emergency response operations to hazardous agents such as a chemical or nuclear event have also been utilized (114).

Dombroski et al. conducted a comprehensive model of a radiological dispersal event complete with analysis of physical dispersion, evacuation and transportation of mass casualties. They found that evacuation participation held a negative correlation with mass casualty management due to traffic disruption of ambulance transportation. They also found that decontamination of patients prior to transport increased trauma fatalities but lack of decontamination of patients potentially added stochastic risk of cancer for first responders (115). Lewis et al. also note that modeling of response polices in a more comprehensive approach to a nuclear event which include communication, health, transport and evacuation is more effective, as the interaction of behaviors and movements of individuals cascade beyond a single policy and affect the larger agent dynamics of the response (116). Computational modeling is particularly well suited to disaster management as disasters affect society at a multitude of levels and modeling of a single response policy does not reflect the influence of one policy on the larger network of emergency response activities.

2.3 Radiation Dread and Risk Perception

The concept of risk is an objective, calculable value which can be determined for a given scenario based on factual data and statistical probability. Yet, when applied within the human context *perception* of risk often differs from the absolute objective value of the actual risk. In practical application calculation of risk is inherently influenced by the perceptions of the individual. From a psychological perspective, each person functions within a reality which they construct, and they evaluate risk intuitively. Intuitive risk perception is subject to “how information on the source of risk is communicated, the psychological mechanisms for processing uncertainty, and earlier experience of danger” (117). Theories of decision making under risk conditions include the “risk-as-feeling” paradigm which holds that “emotional reactions to risky situations often diverge from cognitive assessments of those risks” leading to behavior not based on objective cognitive evaluation of risk but emotions (118). For example, the annual risk of dying in a car crash is approximately 1:6700 whereas the annual risk of dying in an airplane crash is 1:480,000. Yet in society, fear or anxiety for flying is far greater than that for driving a car. This reflects the disparity between statistical risk probability compared to perceived risk (119).

Multiple factors influence evaluation of risk. These factors include an individual’s familiarity with the risk source, their voluntary acceptance of the risk and ability to control their personal exposure to the risk, whether the risk has the potential to be fatal or catastrophic , the degree of irreversibility of the impact, its effect on future generations, the collective societal experience with the risk and the trustworthiness and clarity of information available relevant to the risk. Though different cultures may be shown to have differences in how they calculate different types of risks, studies have shown that the factors which affect perception of risk remain universal (120).

Dreaded risks are a class of risks which are associated with particularly strong emotions of fear, anxiety, and avoidance behaviors. Such risks usually share characteristics which make them invisible and limitless. A risk agent that cannot be visibly detected and without known or predictable boundaries, both in terms of physical space and longevity of the impact increase the dreaded nature of the risk (121). Types of risk illustrative of this phenomenon include exposure to biological, chemical, radiological or nuclear agents (CBRN). In these scenarios, the agent is invisible to the naked eye and the spread or contamination of the agent and the length of the time for incident resolution is inherently unknown. This contrasts with more conventional forms of risk such as naturally occurring phenomena, including floods and hurricanes, where the hazard can be readily detected, and resolution of the event follows a relatively predictable timeline. With CBRN agents, the unbounded nature of the event is also rooted in the stochastic risk of potential for unknown long-term health effects. CBRN events also are not limited to causing conventional physical forms of damage such as with a natural disaster, but also cause contamination. This contamination may be invisible and has the potential for incalculable levels of physical, psychological, environmental or economic damage (122). For perception of risk in rare random events, such as a CBRN event, statistical probability has also been shown to play almost no role at all. For these types of scenarios, it is the inherent unpredictability or randomness of the occurrence that holds the greatest influence in risk perception (120).

Radiation is viewed as a particularly dreaded risk due to the shared cultural experience of nuclear weapons and industrial accidents, its invisible nature which compromises the voluntary acceptance of risk and control over personal exposure, its potential to be fatal and of catastrophic proportion, its potential for long term impact on future generations and the environment, its potential cancer risk, widespread unfamiliarity and lack of knowledge regarding radiation science, and lack of trust in available government information sources. Radiological and nuclear events are hallmark examples of dreaded risk events and the perception gap between statistical values of risk from radiation exposure such as a “dirty bomb” (conventional explosive laced with radioactive isotope), nuclear power plant disaster, or nuclear weapon detonation and the emotional assessment of that risk is widely discussed within the radiation health sciences community (123-128).

Risk perception for radiation exposure is complicated by the multiple types of radiation exposure and the effect of experience and level of knowledge regarding radiation. For example, one study found that risk perceptions regarding different types of radiation exposure varied between the common public and radiation experts. The experts held that naturally occurring forms of radiation such as radon gas in homes and sources of radioactivity used in the medical industry for diagnostics such as X-rays were of higher potential risk than nuclear power or radioactive waste from the nuclear industry. The general public held attitudes in the reverse (121). This may be due to the shared societal experience of nuclear industry accidents such as Three Mile Island, Chernobyl, and Fukushima which are rare, random, and unfamiliar events. The low perceived risk of medical procedures may reflect the cultural acceptance of this form of radiation exposure, the perceived medical benefit, and greater trust in the handlers of the technology (medical professionals vs. nuclear industry professionals). Risk of radon gas exposure was generally regarded with the apathy sometimes seen with other naturally occurring forms of risk like flooding or a hurricane, i.e. "that may be a risk for someone else but probably not for me" (121). Technological disasters also engender a greater perception of dread as compared to natural disasters as manmade disasters are perceived as fundamentally avoidable whereas many natural disasters are perceived as acts of God (122).

2.4 Radiation Dread and Emergency Response

The perception of radiation as a dreaded risk plays an integral role in emergency response for mass casualty management during radiological and nuclear events. First, based on available evidence from the few radiological or nuclear disasters which have occurred, compliance of the general public with government issued protective action guidelines (PAG) is not assured. In the Three Mile Island incident in 1979, for example, only young children and pregnant women within a five mile radius of the plant were advised to evacuate, approximately 3,500 people. Other members of the population were advised to shelter in place and this guideline was only issued in an abundance of caution as no significant environmental releases of radiation actually occurred. Yet, what followed was a mass voluntary evacuation of approximately 140,000 people as the recommended PAG was ignored. Failure to shelter in place during a real radiological or nuclear event will result in very significant numbers of unnecessary radiation exposures.

Large evacuation “shadows,” or additional unnecessary voluntary evacuations, will also compromise transportation routes and the mobility of first responders causing further loss of life (122, 129, 130).

The phenomena of the “worried well” is also a key planning challenge for emergency response for events involving radioactive materials. In the radiological incident in Goiania, Brazil, where a radiation source was accidently exposed within a local community, health officials set up a reception center for those members of the population who wished to be screened for contamination. They were overwhelmed with over 120,000 people, of which only 250 were found to have been contaminated (89, 90). The ‘worried well’ phenomenon directly arises from elevated perceptions of risk associated with radiation exposure and the dreaded nature of radiological or nuclear event scenarios.

The ability of the public to understand basic science terminology and its lack of trust in official information sources remains a significant factor affecting perceptions of risk regarding radiation exposure. A general lack of literacy in basic radiation physics concepts in both the general populace and professionals with higher education contributes to increased dread regarding radiation risk (131-133). A lack of trust in official information sources during previous disasters involving radiation exposures, as occurred with Three Mile Island and Fukushima, also contributes to increased uncertainty and risk perceptions (126, 132-137).

Lack of consensus amongst radiation professionals as to what is a “safe dose” further complicates communication of information regarding risk of radiation exposure (138). Efforts to develop better communication methods with the public following a future radiological or nuclear event are ongoing (132, 133, 139, 140). This includes establishment of preferred government communication sources as one recent study showed that the U.S. public held the highest degree of trust in the CDC to provide accurate information (139). Consequently the CDC has developed communications tools for radiation exposure including their colormetric Radiation Hazard Scale to simplify communication of complex radiation dose information (141). Other methods of communicating radiation dose not in scientific terms but in more conventionally familiar terms have also been suggested. This includes approaches which do not give a numerical dose, but a dose in familiar terms, such as how much radiation a person receives in a single transatlantic plane flight or from eating naturally occurring radioactive potassium in a banana (142, 143). Uncertainty and ambiguity in information sources for radiation health impact serve to increase radiation as a dreaded risk.

The psychological impact of radiation exposure in a radiological or nuclear event represents one of the greatest consequences of this form of disaster and carries perhaps the greatest costs or burden on the affected community. Long-term anxiety from a past received radiation exposure and its potential effect of future incidence of cancer has been well documented in Goiania, Chernobyl, Three Mile Island, and Fukushima (122, 144-147). There is also associated societal stigma from being exposed or contaminated with radiation, both long term and during the immediate emergency response. In Goiania, for example over 8,000 certificates were provided certifying that individuals were free of radioactive contamination. Individuals needed these certificates in order to gain admission to hotels, means of transportation such as buses and planes, and medical treatment as people from that region were refused basic services for fear that they were radioactive (89). Similarly, in Fukushima, individuals received documentation certifying they were free of contamination in order to be able to use taxis or hotels (148). In some cases, elderly evacuees were refused medical treatment due to fear that they were contaminated (149). Evacuees relocating to other regions of Japan have also reported widespread discrimination and are faced with the stigma of being potentially permanently contaminated (121, 150). Following the Goiania incident, discrimination was also reported to extend towards the first responders who aided the victims of the accident, resulting in long term psychosocial effects (151).

2.5 Radiation Dread and First Responders

As illustrated by the comprehensive work of Veenema et al., the potential for radiation dread to affect the performance and efficiency of first responders and other medical personal during a mass casualty event is a real concern (152). First responders are most concerned about events which hold the highest degree of uncertainty or unfamiliarity. Several recent surveys of first responders ranked nuclear and radiological events as highest on a range of disaster scenarios for level of fear and unfamiliarity, and lowest in terms of perceived confidence to respond (123, 153). Key issues which may contribute to this perception are lack of familiarity with both the science and the technologies which would be used during emergency response to this type of disaster. Firstly, there is lack of information and training within the first responder and medical community regarding relative personal risk to radiation exposure and secondly a widespread lack of knowledge for radiation injury specific medical management (125, 154-157). For example, a survey of emergency medicine physicians across the United States showed that only a third had received any form of radiological preparedness training in the last five years. Additionally, irrespective of having received medical training specific to radiation injury, 65% reported that they would not provide medical care even to critically injured victims prior to decontamination (131). A recent survey study by Rebmann et al. similarly reported that first responders' knowledge of radiation exposure and radiation injury specific triage was very low with most respondents having received little or no training to respond to radiological event scenarios (157).

These findings were highly similar to another study using focus groups of emergency department physicians and nurses. The majority of the participants reported a lack of training for radiological events and a third of participants expressed concern for treating contaminated patients and stated these patients should be triaged outside before hospital admittance. In addition, personal protection was reported as a major concern for responding to an emergency where radiation was present. Participants expressed concern for their personal safety, an unwillingness to accept any level of personal radiation exposure, and uncertainty regarding availability of appropriate personal protective equipment for radiation hazards (129).

A separate survey study of factors affecting nurses' willingness to come to work during a radiation event reported a majority of respondents had some degree of willingness to respond in certain scenarios, but 15% of respondents stated unwillingness to respond to any form of major disaster involving radiation. This study found a small but positive correlation between the level of knowledge of radiation injury and willingness to come to work, but a significant correlation between willingness to respond and perception of personal safety (155). Other survey studies of physicians and first responders in the United States and Japan reported similar findings regarding lack of psychological readiness for responding to a radiological or nuclear event, working in contaminated areas or with contaminated patients, and ranking radiological or nuclear events the highest amongst CBRN types of disasters as influencing their willingness to work (158, 159).

One major factor also reported to affect willingness to come to work during an event with radiation was ability to verify the safety of family members. Other surprising findings from these studies were that the availability of dosimetry and the trustworthiness value of guidance information were not ranked above availability of personal protective equipment in terms of willingness to treat patients (129, 158). In addition, one study found that even medical personnel with experience working with radiation such as radiologists and X-ray technicians, similarly described a lack of willingness to respond to a nuclear or radiological event scenario (149). This may be due to unfamiliarity with other forms of radiation exposure and the threat of contamination. New approaches to improving access and tailored curriculum for health provider training for mass casualty management of radiological and nuclear events are being developed but these programs have yet to be implemented on a widespread basis (158-164). A summary of relevant studies examining first responder and other medical personnel willingness to work during a radiological or nuclear event are summarized in Table 1 (156, 165-172) .

Table 1. Overview of Major Literature on First Responders Willingness to Respond to a Radiological or Nuclear Event

(WTW) Willingness to Work, (Rad/Nuc) Radiological or Nuclear event, (~) WTW if asked but not required, (*) 42% WTW without PPE-> 86% WTW if PPE provided, (**)Consistent lack of knowledge/training for medical management of radiation injury or emergency response to events with radiological hazards, (^^) Represents the mean of Dirty bomb/Nuclear scenarios, with or without Rad/Nuc event training from this study

Publication		Year Published	Study Format	Event Type	# Participants	Type of Participant	"Willingness to Work" during a Rad/Nuc Event	Participants "able to perform duties" during a Rad/Nuc Event	Knowledge/ Training = positive association with WTW
"Prepared to Respond? Exploring Personal Disaster Preparedness and Nursing Staff Response to Disasters"	Adams et al.	2020	Survey	Rad/Nuc Event specific	91	Nurses	70%	75%	
"Characterizing Hospital Workers' Willingness to Respond to a Radiological Event"	Balicer et al.	2011	Survey	Rad/Nuc Event specific	3426	All Hospital Staff	61%~	55%	Yes
"Determinants of Emergency Response Willingness in the Local Public Health Workforce by Jurisdictional and Scenario Patterns: a Cross-Sectional Survey"	Barnett et al.	2012	Survey	Rad/Nuc Event specific	2993	Public Health Workers	62%~		
"Improving Hospital Preparedness for Radiological Terrorism: Perspective From Emergency Department Physicians and Nurses"	Becker et al.	2008	Focus Group	Rad/Nuc Event specific	77	ER Physicians / Nurses			
"Readiness for Radiological and Nuclear Events among Emergency Medical Personnel"	Dallas et al.	2017	Survey	Rad/Nuc Event specific	418	First Responders / Physicians	66%	Lack of Rad/Nuc Emergency Management Training**	
"The Willingness of U.S. Emergency Medical Technicians to Respond to Terrorist Incidents"	DiMaggio et al.	2005	Survey	Rad/Nuc Event specific	823	First Responders	74%		Yes
Assessment of Medical Reserve Corps Volunteers' Emergency Response Willingness Using a Threat- and Efficacy-Based Model	Errett et al.	2013	Survey	Rad/Nuc Event specific	3181	Medical Reserve Corps	82%~	68%	

Table 1. cont.

Publication		Year Published	Study Format	Event Type	# Participants	Type of Participant	"Willingness to Work" during a Rad/Nuc Event	Participants "able to perform duties" during a Rad/Nuc Event	Knowledge/ Training = positive association with WTW
"Perspectives of Future Physicians on Disaster Medicine and Public Health Preparedness: Challenges of Building a Capable and Sustainable Auxiliary Medical Workforce"	Kaiser et al.	2009	Survey	Rad/Nuc Event specific	523	Medical Students	84%~	31%	
"Multipatient disaster scenario design using mixed modality medical simulation for the evaluation of civilian prehospital medical response: a "dirty bomb" case study"	Kobayashi et al.	2006	Case study	Rad/Nuc Event specific	48	First Responders		Lack of Rad/Nuc Emergency Management Training**	
"Public Health Department Training of Emergency Medical Technicians for Bioterrorism and Public Health Emergencies: Results of a National Assessment"	Markenson et al.	2005	Survey	Rad/Nuc Event specific	823	First Responders		Lack of Rad/Nuc Emergency Management Training**	
"Disaster Medicine and Public Health Preparedness of Health Professions Students: A Multidisciplinary Assessment of Knowledge, Confidence and Attitudes"	Markenson et al.	2013	Survey	Rad/Nuc Event specific	136	Medical/Nursing/ Dental Students		Lack of Rad/Nuc Emergency Management Training**	
"Health Care Workers' Ability and Willingness to Report to Duty During Catastrophic Disasters"	Qureshi et al.	2005	Survey	Rad/Nuc Event specific	6428	All Hospital Staff	57%		Yes
"Firefighters' and Emergency Medical Service Personnel's Knowledge and Training on Radiation Exposures and Safety: Results from a Survey"	Rebmann et al.	2019	Survey	Rad/Nuc Event specific	433	First Responders		82%	Yes
Comfort level of emergency medical service providers in responding to weapons of mass destruction events: impact of training and equipment.	Reilly et al.	2007	Survey	Rad/Nuc Event specific	823	First Responders		Lack of Rad/Nuc Emergency Management Training**	Yes

Table 1. cont.

Publication		Year Published	Study Format	Event Type	# Participants	Type of Participant	"Willingness to Work" during a Rad/Nuc Event	Participants "able to perform duties" during a Rad/Nuc Event	Knowledge/ Training = positive association with WTW
"Willingness of staff to report to their hospital duties following an unconventional missile attack: a state-wide survey"	Shapira et al.	1991	Survey	Unconventional Missile Attack	1352	All Hospital Staff	42%*		
"Radiological preparedness-awareness and attitudes: A cross-sectional survey of emergency medicine residents and physicians at three academic institutions in the United States"	Sheikh et al.	2012	Survey	Rad/Nuc Event specific	113	Physicians	$79\%^{\wedge\wedge}$	Lack of Rad/Nuc Emergency Management Training**	Yes
"Fear, Familiarity, and the Perception of Risk: A Quantitative Analysis of Disaster-Specific Concerns of Paramedics"	Smith et al.	2011	Survey	Rad/Nuc Event specific	175	First Responders			
"Determinants of Paramedic Response Readiness for CBRNE Threats"	Stevens et al.	2010	Survey	Rad/Nuc Event specific	663	First Responders		Lack of Rad/Nuc Emergency Management Training**	Yes
"Willingness to Respond to Radiological Disasters Among First Responders in St. Louis, Missouri"	Turner et al.	2020	Survey	Rad/Nuc Event specific	433	First Responders	$68\%^{\sim}$	82%	Yes

Table 1. cont.

Publication		Year Published	Study Format	Event Type	# Participants	Type of Participant	"Willingness to Work" during a Rad/Nuc Event	Participants "able to perform duties" during a Rad/Nuc Event	Knowledge/ Training = positive association with WTW
"Radiation Injury Treatment Network Medical and Nursing Workforce Radiation: Knowledge and Attitude Assessment"	Veenema et al.	2020	Survey	Rad/Nuc Event specific	1479	Physicians / Nurses	64%	Lack of Rad/Nuc Emergency Management Training**	Yes
"National nurse readiness for radiation emergencies and nuclear events: A systemic review of the literature"	Veenema et al.	2018	Literature Review	Rad/Nuc Event specific	N/A	All Hospital Staff		Lack of Rad/Nuc Emergency Management Training**	Yes
"Factors Affecting Hospital-based Nurses' Willingness to Respond to a Radiation Emergency"	Veenema et al.	2008	Survey	Rad/Nuc Event specific	668	Nurses	85%	Lack of Rad/Nuc Emergency Management Training**	Yes

These findings illustrate probable complications in mass casualty treatment of those injured during a radiological or nuclear event. As a significant percentage of responding medical personnel may not show up to work, be delayed in reporting for work due to efforts to verify safety of family members or be unwilling to treat critical patients without decontamination, negative effects on patient outcomes can be anticipated. For example, staff shortages of up to 62% were reported in the major hospitals surrounding Fukushima which peaked at one month following the event but continued for 18 months post-event (173). The importance of education and communication are highlighted, as the current consensus guidance amongst radiation injury subject matter experts is that there is minimal risk from radiation exposure to medical personnel in the treatment of critically injured patients contaminated with radioactive material. Current guidelines emphasize that decontamination should take place only after a patient has been stabilized and should not interfere with critical care. The majority of external contamination can be removed by simply removing the patients clothing (129, 158, 161). The findings of one study using focus groups consisting of nurses and physicians reported that participants, upon hearing of this consensus recommendation to stabilize critically injured patients before decontamination, expressed high levels of anxiety and arguments against the policy and some declarations of outright refusal to follow the guideline (129). In another study where respondents were asked what they believed their relative risk to be in treating patients contaminated with radioactive materials, the results included a wide distribution of responses from "no risk" to "high risk" to "do not know." Additionally, over 90% of respondents were unaware that there has yet to be a single recorded incident of a healthcare worker being injured from treating a patient contaminated with radioactivity (158). This lack of awareness can also be exacerbated by perpetuation of misinformation in continuing education programs as at least one guideline for nurses' states that no care should be given to victims of nuclear or radiological terrorism until decontamination procedures have been performed (174). Figure 1 summarizes key findings from the literature regarding willingness to work of first responders.

Key Findings from Literature on First Responders Willingness to Work During a Rad/Nuc Event
Rad/Nuc event ranks highest for lack of willingness to work amongst CBRN event scenarios [6, 152, 153, 158, 165]
Rad/Nuc events ranked highest amongst disaster event scenarios for degree of fear/unfamiliarity [123, 152]
Provision of personal protective equipment had a positive association with willingness to work [152, 168, 170]
Participants stated refusal to follow triage guidelines for contaminated patients [129]

Figure 1. Key Findings from Literature on First Responders Willingness to Work During a Radiological or Nuclear Event

Clearly the need for greater education on medical management of patients with radiation exposures and communication of hazard specific information regarding personal risk in the medical and first responder communities are needed (175, 176) . This education needs to be integrated at all levels of medical management including physicians, nurses, first responders and to some degree for hospital staff. It is not enough to educate only the physicians and first responders as many more nurses and general support staff are needed than physicians for care in a mass casualty setting and a lack of willingness to respond may be greater in these groups (149). One study looking at hospitals workers' willingness to respond to a radiological event whose survey population included participants from general hospital staff at John's Hopkins reported only 39% respondents willingness to respond (4). In addition to formal training programs, the need for "just-in-time" basic protocols and real time information on radiation exposure hazards during the event will be needed (149). As several studies reported a positive correlation between willingness to work and level of training for radiological or nuclear events, such education can be expected to improve participation and implementation of current medical management guidelines for an event involving radiological hazards (Table 1).

Utilization of existing radiation specific SME in the form of certified health physicists, medical dosimetrists, and other medical professionals in radiology and radiation oncology who are experienced in working with radiation is needed (177-180). Further, onsite radiation specific SME could play a critical role in providing and interpreting information on relative radiation risk to emergency response personnel. The Radiological Operations Support Specialist (ROSS) program was recently created to help integrate these experts into emergency response and other efforts to improve communication to first responders and to the public on radiation specific hazards, are ongoing (181-186).

The influence of radiation as a dreaded risk is perhaps the most significant challenge for emergency response to a mass casualty radiological or nuclear event. Perceptions of risk influence willingness to follow protective action guidelines, willingness to come to work, willingness to provide aid to those who may be contaminated and other key behaviors of both the public and professionals during this unique form of disaster. Additional studies are needed to develop policies and planning guides to address these challenges to ensure the most favorable outcomes in medical management of future events involving radiation exposure.

CHAPTER 3 – METHODOLOGY

3.1 Agent-based modeling

Agent-based modeling (ABM) is particularly suited for simulating human systems and understanding emergent social behavior. ABM allows the user to construct bounded artificial environments in order to test hypothesis and build theory. The user can specify the number and type of agents in the simulation, direct the parameters by which they behave and observe subsequent interactions over time. The power of ABM is found in the ability to observe emergent behavior, or the collective trend of behavior which occurs when independent agents interact with each other and within their environment. The phenomenon of emergence is observed when the aggregation of individual behavior on a small scale yields a very different collective behavior. For social psychology, ABM is useful for its ability to segregate or manipulate discrete psychological processes which contribute to larger social phenomena (187). It is also useful to model *actual* behavior patterns against hypothesized *expected* behavior patterns based on the hierarchy of command structure for the agents, and flexibility of key variables in the simulated environment (188). Use of if/then rules can be used to direct individual agent behavior based on influence from the social context of what other nearby agents are doing using numerical thresholds to create a flexible system over time. (189). One area of social interaction that remains ill-defined is how patterns of collective action which benefit the group emerge in the context of negative associated individual costs. Such collective actions may be initiated by a small proportion of leaders and guide net positive outcomes for the population at the cost of less favorable outcomes for the individual participants. Such decision making process are not well understood and are particularly suited for ABM (190). The proposed modeling scenario for this study of first responders accepting personal risk from radiation exposure to provide emergency services to the larger population fits within this type of social interaction.

Some of the weaknesses of ABM are inherent to any modeling platform as simulations are essentially artificial representations and bounded by the dictates of the user. ABM systems are also bounded by scale, number of agents and the degree to which the environment is based on real world data. Use of GIS has been leveraged in many ABM studies to mitigate this limitation (191). However, ABM is essentially a micro-environment designed to examine how emergent social behavior arises from relatively simple agent directed rules. Emphasizing minimality in the structure of the model and directed agent behavior remains the strength of agent-based simulations. The advantage of ABM is found in its bounded simplicity which enables a clearer view of how complex social behaviors can be driven by simple individually acting agent interactions (192).

3.2 NetLogo

NetLogo is a “multi-agent programming language and modeling environment for simulating natural and social phenomena”(193). It is a well-established agent-based modeling platform which is designed to be used for research and education (194). Though it is simple enough to be used by users who lack an explicit programming background, its versatility has been leveraged for use in advanced modeling studies. NetLogo was written in Java so it is widely compatible, it is freeware and has a robust library of online resources to aid in model development. The NetLogo language is structured in Lisp format to support concurrent agents that operate autonomously. In NetLogo, agents are referred to as “turtles” and the environment they move over are called “patches.” Both the turtles and patches are programmable agents. All agents are able to simultaneously interact with each other and execute pre-programed tasks within the boundaries of the structured environment. The “observer” is also a programming context which can be used to execute commands which are applied to “all turtles” or “all patches.” Output data from the model can be structured according to the user’s needs and tailored metrics (193, 195).

3.3 Model Structure in NetLogo

The NetLogo models for this study were coded “from scratch” to build unique agent-based and model environment-based interactions. Within each model, each agent interaction is unique to that agent's own individual interaction with other surrounding agents and the model environment. For this study, two model series were used to explore the effect of radiation dread on first responders 1) willingness to enter an area with radioactive contamination or 2) triage patients with radioactive contamination.

The Model 1 series, First Responders Willingness to Enter an Area with Radioactive Contamination, includes two base models: Model 1A: First Responders with Pocket Dosimetry and Model 1B: First Responders with SME. Model 1A: First Responders with Pocket Dosimetry assumes first responders responding to an emergency with radioactive contamination in the field have handheld radiation dosimetry. Model 1B: First Responders with SME assumes first responders responding to an emergency with radioactive contamination in the field have the addition of radiation subject matter experts (SME) present.

The Model 2 series, First Responders Willingness to Triage Patients with Radioactive Contamination includes two base models: Model 2A: Triage with Pocket Dosimetry and Model 2B: Triage with SME. Model 2A: Triage with Pocket Dosimetry assumes first responders in a triage scenario where patients with radioactive contamination require medical treatment have handheld radiation dosimetry. Model 2B: Triage with SME assumes first responders in a triage scenario where patients with radioactive contamination require medical treatment have the addition of radiation (SME) present.

3.3.1 Model 1 Series Structure: First Responders Willingness to Enter an Area with Radioactive Contamination

The premise of this model series involves a population of first responders responding to an emergency with radioactive contamination. "First responders" in this scenario may include firefighters, police persons and emergency medical technicians (EMT). In the model with added radiation SME, SME's in this scenario may include trained health physicists or represent firefighters, police or EMT's with radiation hazard specific training. As shown in Figure 2, I model is designed with a starting agent population randomly generated within a constrained area within the lower region of the model environment. First responder agents are colored green and SME agents are colored red. The upper region of the model depicts an area with radioactive contamination including both a point source of radiation and a fallout area using a Poisson distribution. This simulates key aspects of likely scenarios involving radioactive contamination.

Movement in this model series involves agent directed movement/interaction based on an established NetLogo "boids" or "flocking" algorithm (195). This algorithm simulates the natural movement of birds in flight where agents, or "boids" move in association with each other. This code which allows overall group movement while also allowing individual movement was modified specifically for the current model, to simulate agent-based interactions and movement to simulate social gathering interactions of first responders in the field. The model code directs agents to form loose social groupings based on random associations between agents in their immediate respective environments. Each agent is also assigned a “myradiationtolerance” value. This variable is designed to represent each first responder agent’s familiarity and comfort level with radiation exposure and is coded on a scale of 1-5. This numerical coding was selected to mirror the survey response values from an external dataset evaluation of first responders’ willingness to respond to an emergency with potential exposure to radiation. This external dataset is discussed further in Section 3.5 External Dataset. For the purposes of this model series, SME agents were assigned a myradiationtolerance of [10] or twice the value of the highest survey value score.

Key variables in this model series include the starting population size of the first responders and SME, each agent’s myradiationtolerance value and the communication distance (patch distance) over which agents can exchange their myradiationtolerance information. Agents are directed to form social groups while approaching the area with radioactive contamination. Speed of the respective agents is dictated by each agents’ respective myradiationtolerance variable with increasing speed associated with higher myradiationtolerance score and an additional speed boost when the average myradiationtolerance of an agents’ group (myRT) is $\geq$ [2.5]. The variable “myRT” represents the mean of the myradiationtolerance values (myRT) for a given social grouping. The size of the grouping is determined by the settings for the communications variable i.e., with increasing communication (patch distance) there is a larger associated group and larger (n) for the (myRT) value. In this model, when an individual agent determines the mean myRT for their surrounding group their own myradiationtolerance value is excluded from that mean so that additional speed boost is a result of their surrounding neighbors added to their own base speed value. Yet if the mean myRT value is below the threshold there is little additional speed boost, so the influence of surrounding neighbors may have a positive or negative effect. Measurable output for this model series is quantification of the number of first responders entering the area with radioactive contamination within a standardized model time window of (900 steps). A summary of Model 1 series variables and their coded function are included in Table 2. Sample visual snapshots of Model 1A: First Responders with Pocket Dosimetry and Model 1B: First Responders with SME are depicted in Figure 2 and Figure 3 respectively and demonstrate model setup/initiation and agent-based movement and social groupings.

Table 2. Model 1 Series Structure: Key Coding Variables

Model 1 Series Structure: First Responders Willingness to Enter an Area with Radioactive Contamination	
	Key Coding Variables
Agents	
First Responders	agent set in Model 1A/B
SME	agent set in Model 1B
Agent variables	
nearest-neighbor	reports nearest flockmate
flockmates	other agents within the set communication radius
myRadiationTolerance	assigned value
myRT	mean [mineRadiationTolerance] of flockmates
Patch variables	
communication	patch distance over which agents can share information
falloutZone?	this variable report TRUE or FALSE if a patch is within the designated falloutZone
radiation	a radiation variable is included in the background environment within the contaminated area
pointsourceRad	an additional pointsource of radiation is overlapped within the contaminated area
pcolor	patch color

A)

B)

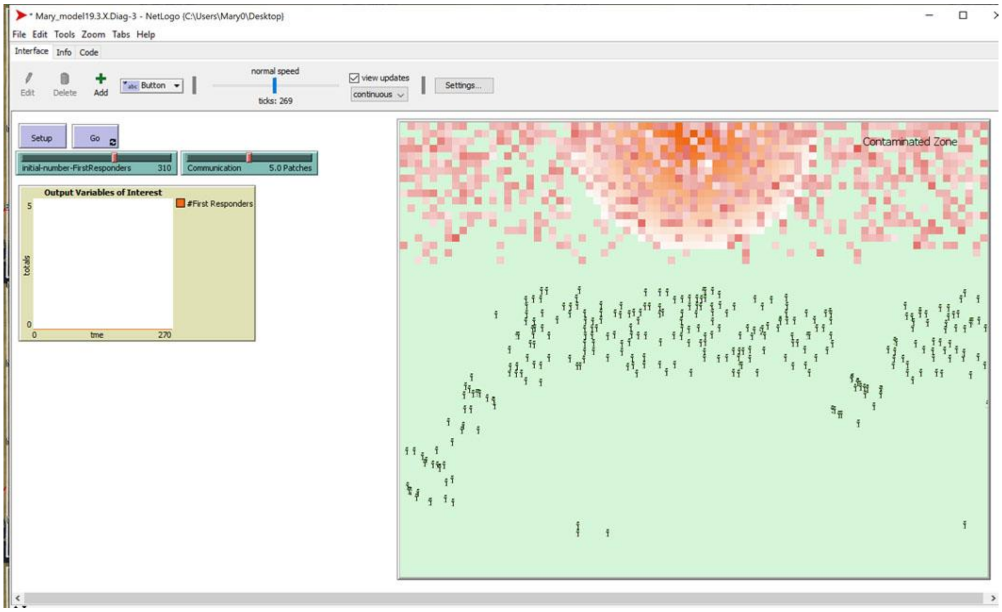
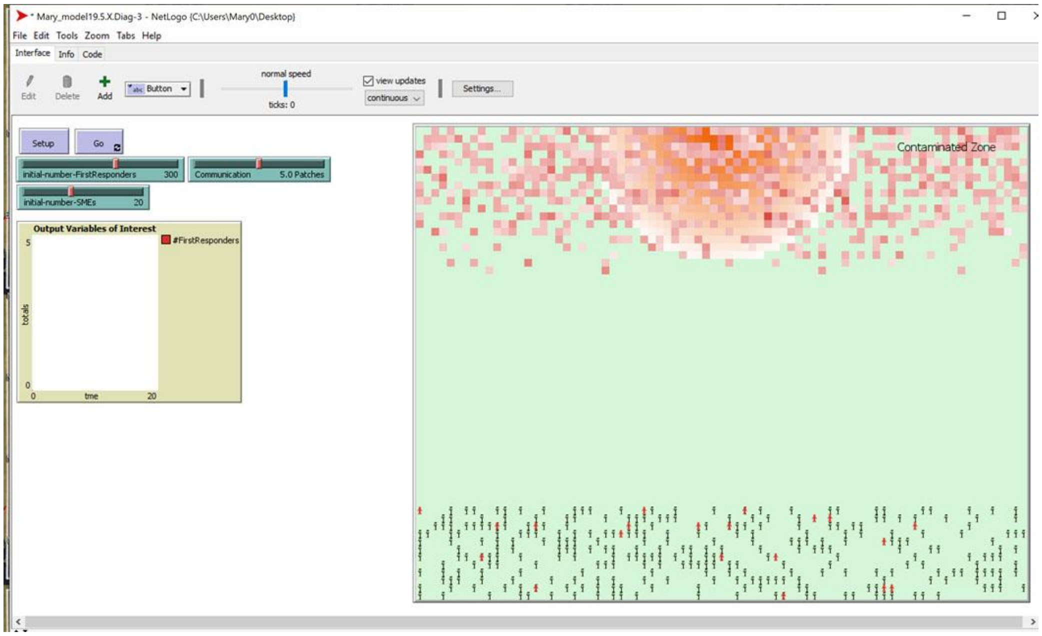


Figure 2. Model 1A First Responders with Pocket Dosimetry: Setup

The starting setup A) of Model 1A depicts a population of first responder agents randomly populated within a constrained area within the lower region of the model environment. The upper region of the model depicts an area with radioactive contamination. Slider buttons can be used to manually alter the initial number of first responder agents and the level of communication (patch distance). The measurable output-variable for this model is number of first responders who enter the area with radioactive contamination. The model in motion B) shows first responder agents forming social groupings and moving towards the area of radioactive contamination. In this model, the only agent population is first responders.

<u>A)</u>



B)

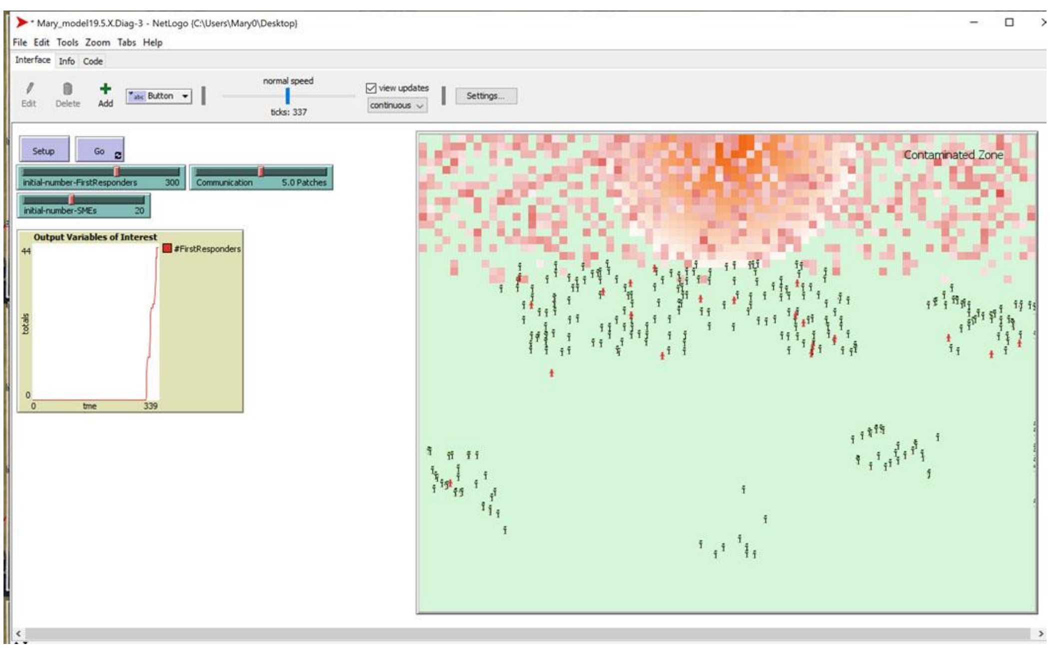


Figure 3. Model 1B First Responders with Radiation Subject Matter Experts: Setup

The starting setup A) of Model 1B depicts a population of first responder agents (colored green) and a population of radiation SME (colored red) randomly populated within a constrained area within the lower region of the model environment. The upper region of the model depicts an area with radioactive contamination. Slider buttons can be used to manually alter the initial number of first responder agents, the initial number of SME agents and the level of Communication (patch distance). The measurable output-variable for this model is number of first responders who enter the area with radioactive contamination. The model in motion B) shows first responder and SME agents forming social groupings and moving towards the area of radioactive contamination.

3.3.2 Model 2 Series Structure: First Responders Willingness to Triage Patients with Radioactive Contamination

The premise of this model series involves a population of first responders involved with mass casualty triage of a patient population potentially contaminated with radioactive contamination. “First responders” in this scenario may include doctors, nurses and emergency medical technicians (EMT). In the model with added radiation SME, SME’s in this scenario may include trained health physicists or medical dosimetrists or represent EMT’s, doctors or nurses with radiation hazard specific training. The model is designed with a starting agent population of first responders or SME randomly generated within a constrained (color coded: yellow) area depicting either an emergency room or medical reception center in the field. A second agent population designed to represent injured civilians contaminated with radioactive materials is randomly generated within a constrained (color coded: blue) area. Exit corridors for “treated” civilian agents are coded in white. First responder agents themselves are colored green and SME agents are colored red. Civilian agents are shaded blue and become lighter or darker based on their respective health variable value. Sample visual snapshots of Model 2A: Triage with Pocket Dosimetry and Model 2B: Triage with SME are depicted in Figure 4 and Figure 5 respectively and demonstrate model setup/initiation and agent-based movement and triage.

In this model series, the first responder and SME agent population have baseline directions to move in a slightly random fashion to simulate persons “milling” or moving slightly randomly about. The civilian agent population is directed to move directly towards the triage area. Civilian agents are initially assigned a “health-status” variable value using a scale of 1-100 with 100 representing perfect health and 1 representing death. Initial health values are assigned using a normal distribution mean set at [50] and with each patch movement forward a reduction in health-status value occurs until the civilian agents reach the (color coded: yellow) triage area. Civilian agents also have a “triage-status” variable which reflects a true/false value whether they have had a triage interaction with a first responder or SME. Each first responder and SME agent are assigned a “myradiationtolerance” value. This variable is designed to represent each agent’s comfort level with radiation exposure and is coded on a scale of 1-5. First responder agents also have a “triage-willing” variable which reflects a true/false value whether they are willing to triage. For “triage-willing” to report TRUE, a first responder must have an individual myradiationtolerance ≥[4] or a “myRT” or mean myradiationtolerance value of their neighbors ≥[4]. The 1-5 myradiationtolerance numerical coding was selected to mirror the survey response values from an external dataset evaluation of first responders' willingness to respond to an emergency with potential exposure to radiation. This external dataset is discussed further in 3.5 External Dataset. For the purposes of this model series, SME agents were assigned a myradiationtolerance of [10] or twice the value of the highest survey value score.

Key variables in this model series include the starting population size of the first responders and SME populations combined vs. the starting civilian population, each first responder and SME agent's myradiationtolerance value and the communication distance (patch distance) over which first responder and SME agents can exchange their myradiationtolerance information. A summary of Model 2 series variables and their coded function are included in Table 3. First responders are directed to "mill" about until a civilian agent moves within a specified range. When a civilian agent comes within range of a first responder or SME agent, the decision to triage algorithm is engaged. This triage algorithm utilizes a "fast and frugal" style decision tree as outlined in Figure 6.

Briefly, if the first responder or SME agent has a myradiationtolerance value $\geq$ [4] and a civilian agent with a health-status variable $<$ [75] moves within range the agent will move towards the injured civilian and perform triage. Triage is structured in the model as the formation of a "link" between the civilian agent and the first responder or

SME agent. According to the triage algorithm, if the civilian has a health-status score < [75] and > [30] the first responder or SME agent will remain stationary and linked to the civilian and increase the agent's health-status score in [.1] increments for every time step which passes. If the civilian has a health-status value < [30] their triage-status variable will report true, but the first responder or SME will not continue to triage that agent reflecting real world triage decision making.   In the model, if a first responder is triaging a civilian, they cannot form links or triage an additional civilian at the same time, though multiple first responders or SME may form concurrent links with the same civilian.   This serves to simulate the time resources involved in treating a patient and the exclusivity of real triage i.e., they triage one person at a time, but you may have more than one first responder working on a single patient.

If the first responder has a myradiationtolerance value < [4], then the first responder is directed to communicate to any other first responders or SME within the set communication distance. If the mean myradiationtolerance (myRT) of these neighbors is ≥ [4], then that first responder (who's own mineradiationtolerance is < [4]) will now follow the decision tree for agents with myradiationtolerance ≥ [4] and follow the subsequent triage algorithm. If the (myRT) value is < [4] then the first responder will fail to engage in triage. In this algorithm, the agents' own myradiationtolerance score is included in the calculated mean myRT of its neighbors. Once civilians have been triaged, if they have a health-status ≥ [75], they are directed to move along the white exit corridors within the triage area and aggregate at the end of the exit corridors at the edge of the model. Civilians who have been triaged with a health-status value $<$ [30] or civilians who have not been triaged irrespective of their health-status value, due to lack of available first responders or SME, line up along the far edge of the model. Measurable output for this model series is quantification of the number of triage-willing first responders and secondary output is number of triage positive civilian agents within a standardized model time window of (4500 steps).

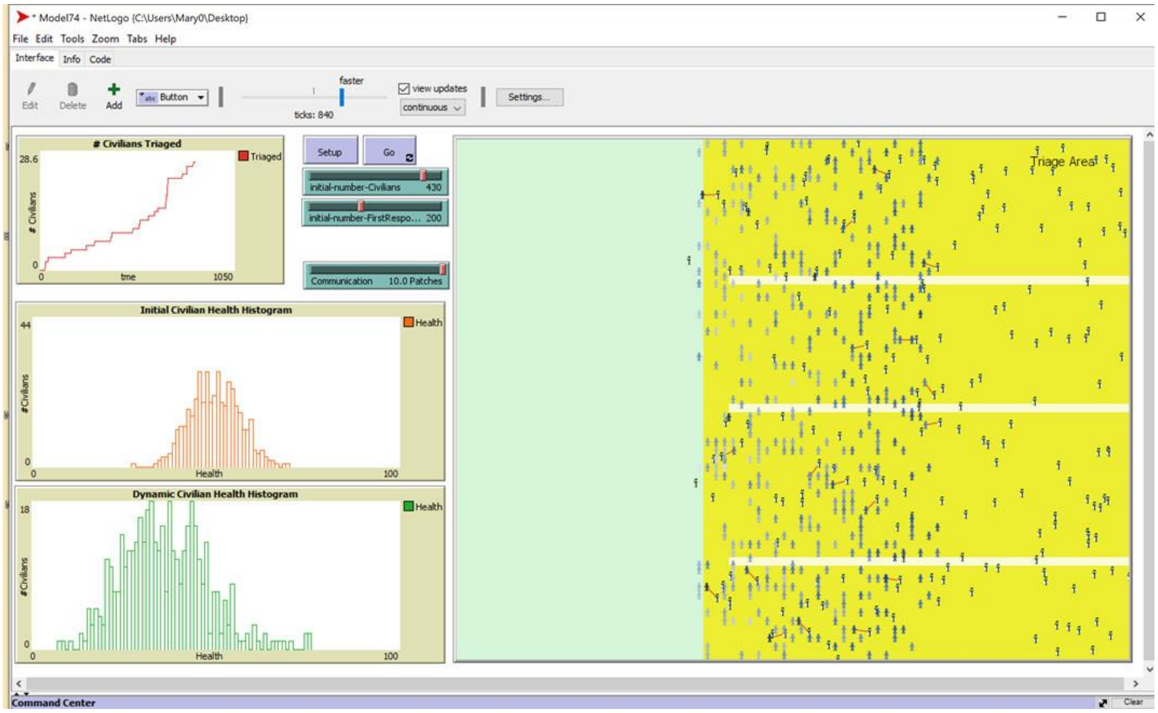
Table 3. Model 2 Series Structure: Key Coding Variables

Model 2 Series Structure: First Responders Willingness to Triage Patients with Radioactive Contamination	
	Key Coding Variables
Agents	
First Responders	agent set in Model 2A/B
SME	agent set in Model 2B
Civilians	agent set in Model 2A/B
First Responder and SME agent variables	
nearest-neighbor	reports nearest flockmate
flockmates	other agents within the set communication radius
myRadiationTolerance	assigned value
myRT	mean [mineRadiationTolerance] of flockmates
triage-willing	reports if agent is willing to triage
Civilian agent variables	
health	numeral score assigned to civilian agents
triage-status	reports if agent has interacted with a First Responder or SME
Patch variables	
communication	patch distance over which agents can share information
pcolor	patch color
triageEnd	designates patch area at the edge of the triage_area
triage_area	desginated patch area where agnet interactions for triage occur

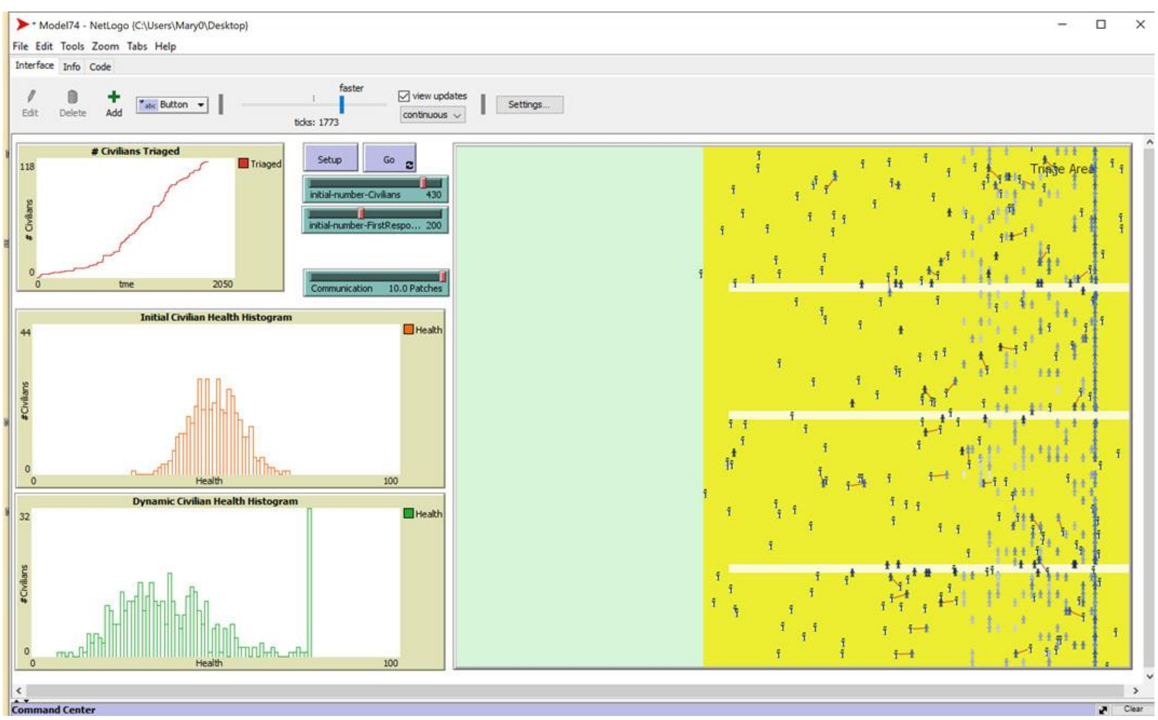
A)


Model74 - NetLogo (C:\Users\Mary0\Desktop)
File Edit Tools Zoom Tabs Help
Interface Info Code
Edit Delete Add
Button
normal speed
ticks: 0
view updates
continuous
Settings...
Civilians Triaged
Triaged
Civilians
time
Setup
Go
initial-number-Civilians 430
initial-number-FirstRespo... 200
Communication 10.0 Patches
Initial Civilian Health Histogram
Health
#Civilians
Dynamic Civilian Health Histogram
Triage Area
Command Center
Clear

B)


* Model74 - NetLogo {C:\Users\Mary0\Desktop}
File Edit Tools Zoom Tabs Help
Interface Info Code
ticks: 840
Setup
Go
initial-number-Civilians 430
initial-number-FirstRespo... 200
Communication 10.0 Patches
Civilians Triaged
Triaged
Initial Civilian Health Histogram
Health
Dynamic Civilian Health Histogram
Triage Area
Command Center

c)


* Model74 - NetLogo {C:\Users\Mary0\Desktop}
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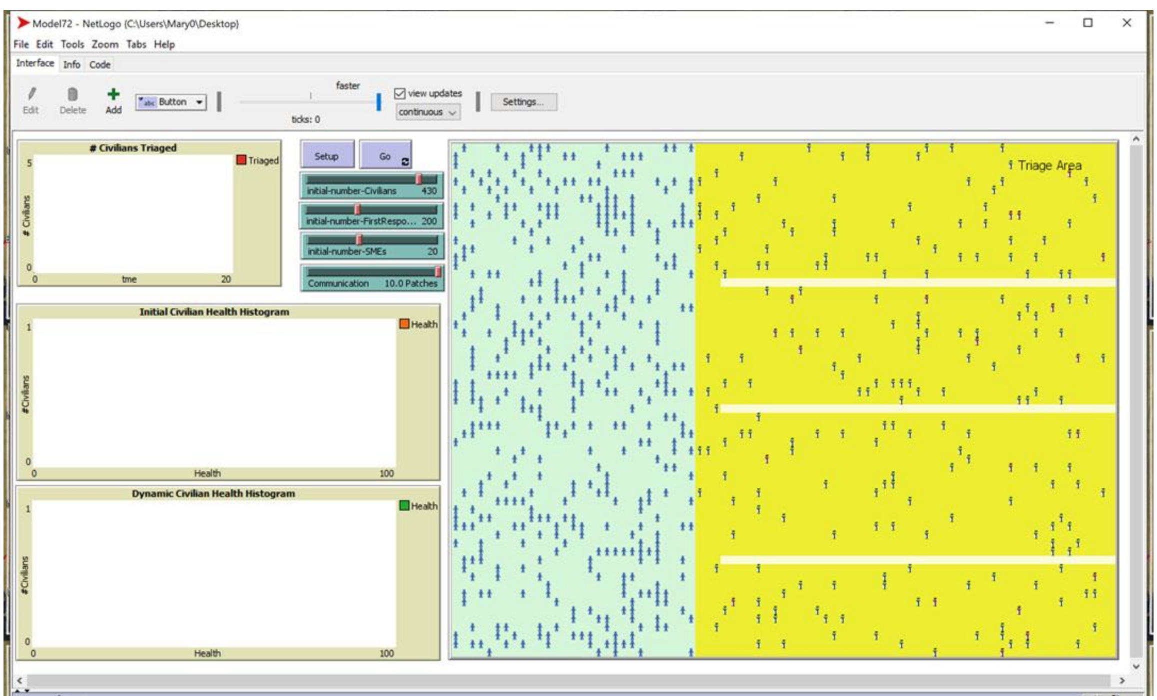
Interface Info Code
ticks: 1773
Setup
Go
initial-number-Civilians 430
initial-number-FirstRespo... 200
Communication 10.0 Patches
Civilians Triaged
Triaged
Initial Civilian Health Histogram
Health
Dynamic Civilian Health Histogram
Triage Area
Command Center

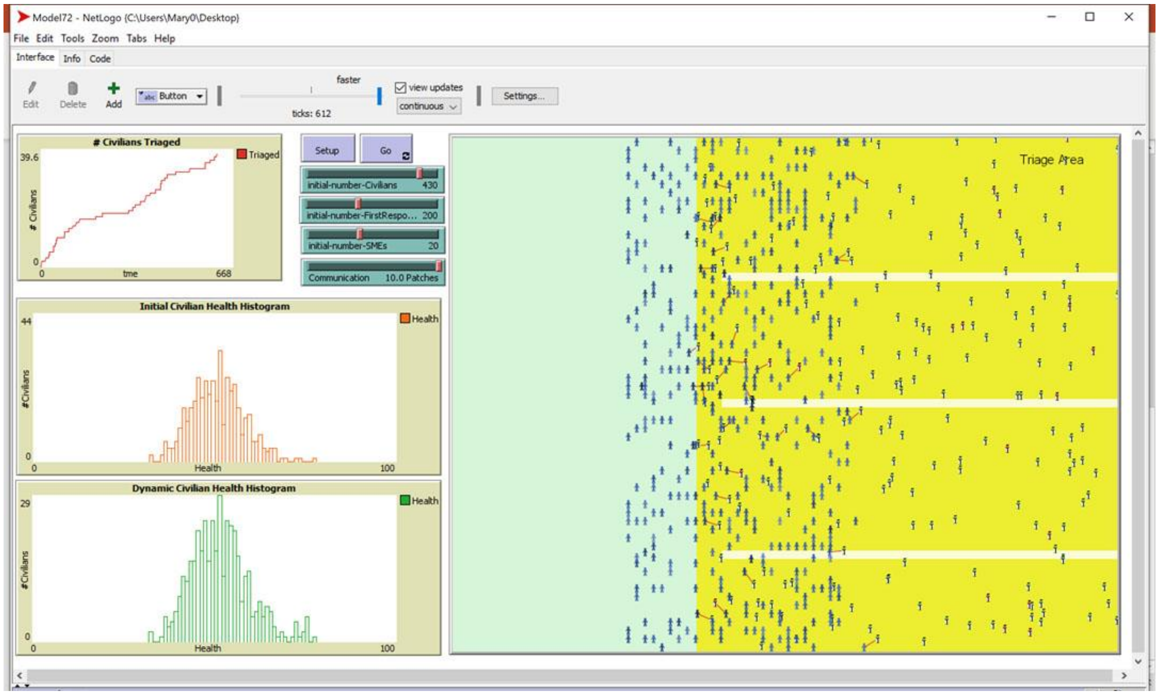
Figure 4. Model 2A: Triage with Pocket Dosimetry: Setup

The starting setup A) of Model 2A depicts a population of civilian agents (colored shades of blue to black based on their health score with a darker blue color associated with increased health) on the left and a population of first responder agents (colored green) on the right within the triage zone (colored yellow). Agents are randomly populated within a constrained area within their respective zones. The model depicts a population of civilians moving towards and entering the triage zone. Slider buttons can be used to manually alter the initial number of first responder agents, the initial number of civilian agents and the level of communication (patch distance). The measurable output-variable for this model is number of triage-willing first responders and number of civilians triaged. The model in motion B) shows first responders interacting with the civilian population and forming triage links (colored red) and C) show civilian agents with health [< 75] will stop when they reach the end of the triage zone and civilian agents with health [$\geq$ 75] will aggregate at the end of the exit corridor. Additional histogram outputs of civilian health distribution have also been added for visual aide.

A)



B)



C)

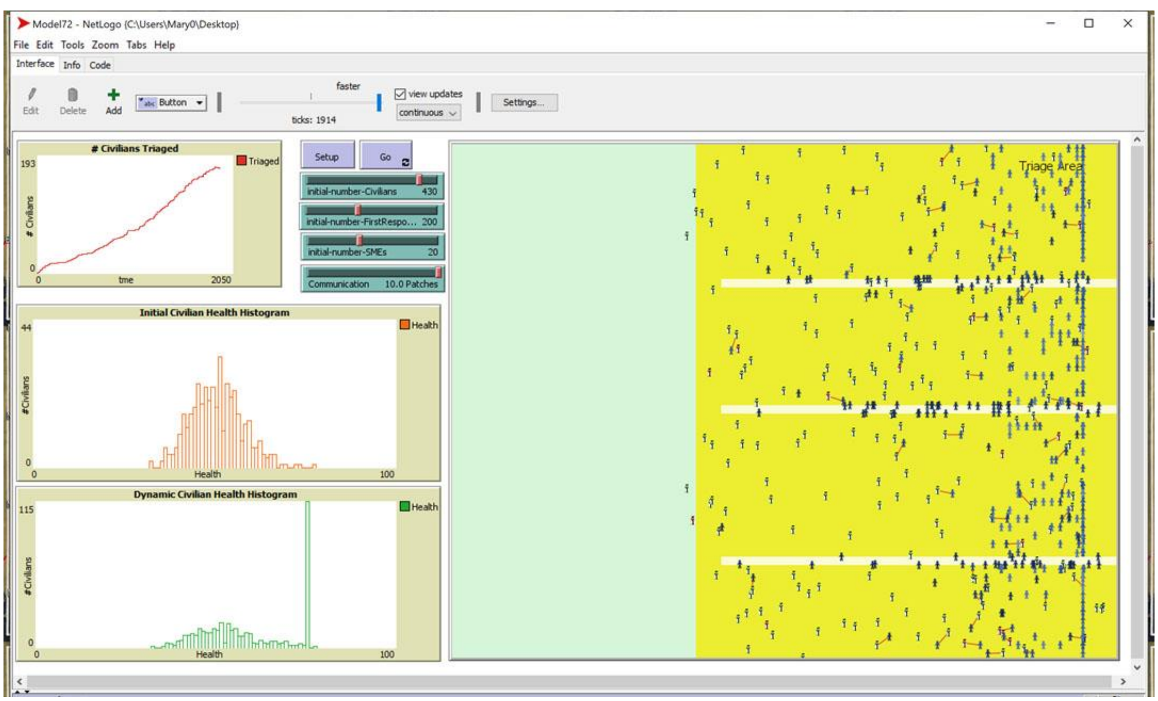


Figure 5. Model 2B: Triage with SME: Setup

The starting setup A) of Model 2B depicts a population of civilian agents (colored shades of blue to black based on their health score with a darker blue color associated with increased health) on the left and a population of first responder agents (colored green) and SME (colored red) on the right within the triage zone (colored yellow). Agents are randomly populated within a constrained area within their respective zones. The model depicts a population of civilians moving towards and entering the triage zone. Slider buttons can be used to manually alter the initial number of first responder agents, the initial number of SME, the initial number of civilian agents and the level of communication (patch distance). The measurable output-variable for this model is number of triage-willing first responders and number of civilians triaged. The model in motion B) shows first responders and SME interacting with the civilian population and forming triage links (colored red) and C) show civilian agents with health [< 75] will stop when they reach the end of the triage zone and civilian agents with health [≥ 75] will aggregate at the end of the exit corridor. Additional histogram outputs of civilian health distribution have also been added for visual aide.

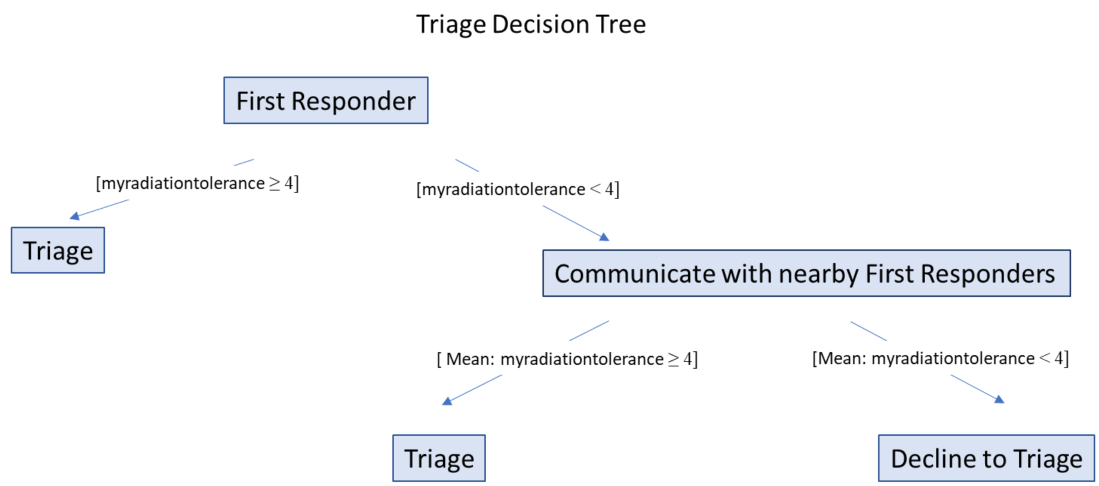


Figure 6. Model 2 Series First Responders Willingness to Triage Patients with Radioactive Contamination: Triage Decision Tree

3.4 Model Testing and Validation

<u>Model Verification</u>

Model *verification* is a key step in any simulation study and utilizes a series of preliminary experiments to validate that the model is functioning as intended (196). Model verification includes validation that agents are applying the intended set of behavioral actions correctly and that the model environment is performing as designed. In the main experimental phase, multiple serial runs were completed to generate sufficient statistical rigor for aggregated data and to ensure consensus in observed phenomena, as each run is essentially unique in its initial generation of agents and subsequent agent interaction. Internal verification that there were no anomalies in seed generated random values was also performed.

Model Calibration

Model calibration which addresses whether the model is integrated with data representing the real world, is achieved through application of human data sets taken from the closest available real-life scenario. For this model series designed to test the effect of radiation dread on first responders' willingness to enter areas with radioactive contamination or to triage civilians with radioactive contamination, a data set was sourced through a data sharing agreement with Terri Rebmann at Saint Louis University, containing survey responses regarding firefighters and emergency response personnel's "willingness to respond" and "comfort level" working in either a dirty bomb event, or where a plume from a radioactive waste fire is present. Survey values from respondents in this study were used to calibrate each respective model.

Model Novel Findings

For each model series in this study, "novel findings" are reported as the novel data and behavioral observations noted under various model conditions using external data set survey values for the model variable "myradiationtolerance." For the Model 1 Series: First Responders Willingness to Enter an Area with Radioactive Contamination, output values are measured in terms of number of first responders entering the area with radioactive contamination, and for the Model 2 series: First Responders Willingness to Triage Patients with Radioactive Contamination, output values are measured in terms of number of triage-willing first responders with a secondary output of number of civilians triaged.

3.5 External Dataset

The external dataset referenced above in Model Calibration and Model Novel Findings consists of the raw data set values collected from a voluntary anonymous survey conducted between July 2018 and February 2019 of firefighters and emergency response personnel associated with two of the largest first responder agencies in the greater St. Louis, Missouri metropolitan area. Of 522 individuals invited to participate in the survey, 433 completed the survey. The survey included a series of questions related to first responders' willingness to respond, knowledge and training, their individual perceived ability to respond and personal risk perceptions to two different radiological event scenarios including:

1) a radiological terrorism event where *"a radioactive (dirty) bomb has exploded in downtown St. Louis. Thousands of people are flocking to emergency rooms throughout the greater St. Louis region. In this scenario, "going to work" means that you will be responding at the scene of the bombing."*

2) a naturally occurring/non-terrorism-related radiological event where *"the subsurface smoldering event (fire) at the St. Louis West Lake Landfill that started in the South Quarry, which contains traditional trash, has now spread into the North Quarry area, which contains discarded radiological waste. After the fire and heat came into contact with the radiological materials, it generated a radioactive plume that is spreading through-out the region and threatening nearby residences. Nearby residents need to be evacuated. In this scenario "going to work" means that you will be responding at the scene for fire control, provision of medical care or helping resident evacuate into a safe area."*

The findings of this survey are characterized in two publications by Rebmann et al. "Firefighters' and Emergency Medical Service Personnel's Knowledge and Training on Radiation Exposures and Safety: Results from a Survey published in 2019 and by Turner et al. "Willingness to Respond to Radiological Disasters Among First Responders in St. Louis, Missouri published in 2020 (3, 157). Through a data sharing agreement with Terri Rebmann, Director of the Institute for Biosecurity at Saint Louis University, access to raw data from the survey was obtained for use in validating the models. This data series represents the best available fit “real world” data for the purposes of modeling radiation dread in the current model series.

Survey respondents were asked to rank their agreement with a series of statements on a scale of 1-5 with (1) Disagree strongly, (2) Disagree somewhat, (3) Neither agree nor disagree, (4) Agree somewhat and (5) Agree strongly. For the purposes of application of these numerical scores within the model, the model myradiationtolerance variable and other code functions on which this variable depends were scaled to meet this 1-5 range. For model calibration, values for the statement Q6_1 for the dirty bomb scenario and Q7_1 for the plume from a radioactive waste fire scenario for the statement: “I would go to work if my employer requested it, even if it was not required” were used for first responder agents’ myradiationtolerance variable. For model novel findings, survey values for the statement Q6_7 for the dirty bomb scenario and Q7_ 7 for the plume from a radioactive waste fire scenario for the statement: “I would feel safe working/performing my normal duties during this event” were used for the first responder agents’ myradiationtolerance variable. For all radiation SME a myradiationtolerance value of (10) or double the highest possible regular first responder myradiationtolerance value was assigned.

3.6 Limitations

Limitations include the fundamental limitations of any abstract computational model. This includes the necessary simplicity of the constructed model, which is bounded by user design, and in the case of the current model, a lack of identical pre-existing mass casualty event scenarios from which to draw reference. Numerical values assigned to variables in the model are also intrinsically arbitrary. For example, there are no established metrics for evaluation or scoring of “radiation dread” in the real-world setting. As data for the variable myradiationtolerance, which might be interpreted, as an individual’s comfort level with accepting radiation exposure does not explicitly exist, the survey respondent values for the statement “I would feel safe working/performing my normal duties during this event” were used as the best surrogate match for the model. Though these values do not expressly represent the variable in question, they can be used as the best correlative match for the current model series, which proposes to illustrate the potential impact of radiation dread of first responders’ willingness to respond and to investigate variables which may mitigate this effect.

Also, numerical health scores (1-100 range) in the model are simplified and somewhat arbitrary assignments and do not reflect the complex nature of combined injury in a nuclear event, which would include the sum effect of blast/thermal/radiation exposure injuries, which may occur concomitantly in a single individual. Use of such a simplified scoring system is necessary due to limitations of scope and complexity for the current modeling study due to time and computing power. Communication values in the current model represent physical distance within the model environment and are used as a surrogate marker for range of communication distance or ability to communicate in a real-world setting. The communication variable is designed to represent ability to share information and may represent a range of communication options including radio/cell phone/internet.

Finally, although modeling of disaster management on a 1:1 scale is ideal for observing population movement and complex system dynamics, the practical limitations of the NetLogo platform limits the number of agents in the proposed simulation to a maximum of 1000 agents. This is a practical limit in consideration of computing power and to retain the ability to visually observe agent-agent interactions. Other practical limitations for the study include the number of runs used to report findings from each data series. Though 50 runs were used for data calculations in the early stages of data generation, it was later determined that the strength of the model allowed for consistent findings with as low as 10 runs. This was a useful approach given the challenges of limited computational power, and the length of time needed per run for the more complex algorithms in the later models.

CHAPTER 4 – RESULTS

4.1 Model 1 Series: First Responders Willingness to Enter an Area with Radioactive Contamination

This computational model series is designed to explore factors which affect first responder's willingness to enter an area where radioactive contamination is present. In Model 1A: First Responders with Pocket Dosimetry, an agent population consisting only of first responders is generated. In Model 1B: First Responders with SME, an agent population consisting of first responders and added radiation SME are generated. Each model was constructed and evaluated through a testing phase or *verification phase*, to verify that the model algorithms were performing appropriately, a *calibration phase* where the model settings were fine-tuned using the external survey data set and a *novel findings* phase, where novel data were generated based on the established reference settings from the calibration phase. The output of both models is measured in the percentage of first responders which enter the area with radioactive contamination present.

4.1.1 Model 1A: First Responders with Pocket Dosimetry

4.1.1.1 Model 1A: Verification

For verification of Model 1A, a range of values was explored for each key variable in the model including the size of the starting population of first responders and the range of communication distance (patches) with which the agents can exchange information. In the verification phase first responder agents were assigned a myradiationtolerance value using a normal distribution in the same numerical range as the external dataset survey values. As shown in Figure 7, the model is performing as expected under a wide range of values. We see a positive correlation between the percentage of first responders entering the radioactive contamination area and the communication variable. This trend is generally proportional of the population size at a communication distance of [2] patches. At communication distance of [5] patches, there is no significant trend with starting population size > [100] on the percentage of first responders entering the radioactive contamination area. At a communication distance of [10] patches there is no significant trend of percentage of first responders entering the radioactive contamination area with respect to starting population size.

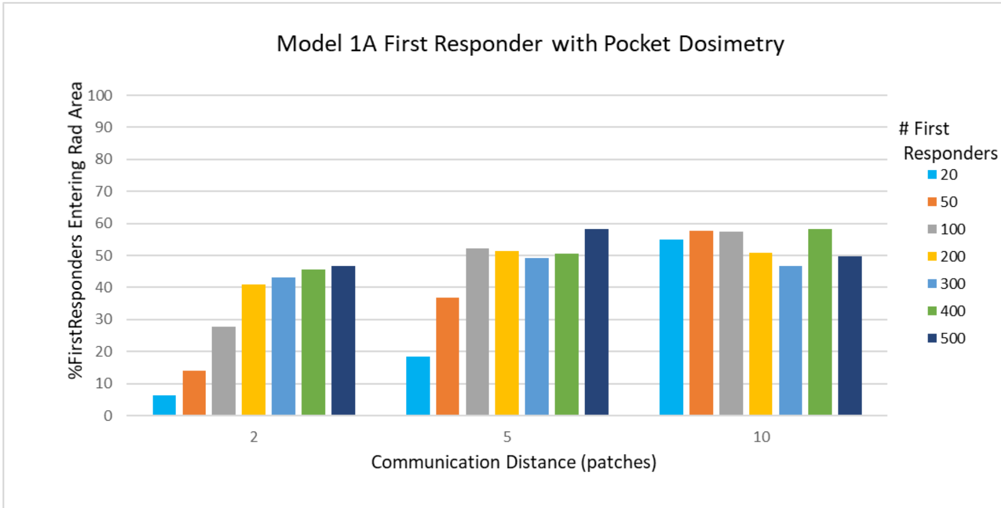


Figure 7. Model 1A: First Responders with Pocket Dosimetry <u>Model Verification</u>

Data represents mean value from 20 runs. Communication distance represents the distance (patches) over which agents can communicate their respective myradiationtolerance variable information. The number of first responders refers to the starting population size of "first responder" agents in the model.

4.1.1.2 Model 1A: Calibration

For calibration of Model 1A, an external data set sourced from the Turner et. al study, which includes survey responses to a series of statements regarding first responders' willingness to work during two scenarios where radioactive contamination is present was used (3). The Q6 scenario involved emergency response to a dirty bomb event and the Q7 scenario involved emergency response to a radioactive waste fire with an aerosolized radioactive plume. From this survey dataset, participant scores for the statement *"I would go to work if my employer requested it, even if it was not required"* translated as “willingness to work” (WTW) were substituted in the model for values for the myradiationtolerance variable and model variables for speed were calibrated so that the percentage of first responders entering the radioactive contamination area in the model matched the reported WTW percentages reported in the survey. This was completed for both the Q6 and Q7 scenarios with a communication distance of [2] patches and a starting first responder population in the model of [433] to match the number of 433 survey respondents one for one. As shown in Table 4, Model 1A for the Q6 scenario, the survey data reported a 68.4% WTW and the model was calibrated to 70% first responder agents entering the radioactive contamination area. For Model 1A for the Q7 scenario, the survey data reported a 73% WTW and the model was calibrated to 73% first responder agents entering the radioactive contamination area. (Table 4)

Table 4. Model 1A: First Responders with Pocket Dosimetry <u>Model Calibration</u>

*the number of agents populated in the model, 433 directly correlates with the # of survey respondents

**patch distance over which the agents can communicate and share their respective mineradiationtolerance values

^myRT is the average of myradiationtolerance of close neighbors

˜final model calibration WTW % represent the mean of 40 runs

Model Calibration with External Data Set: First Responder Survey Data	
Model Calibration to Survey Question:	**WTW**
Q6_1 WTW in Dirty Bomb Scenario	**68.4%**
Model 1A First Responders with Pocket Dosimetry	
Model 1A Q6_1 Calibration Variables	
First Responders starting population [433]*	
Communication Distance [2]**	
Movement speed increase if [myRT >= 3.55]^	70%~
Model Calibration to Survey Question:	**WTW**
Q7_1 WTW in Radioactive Plume from Radioactive Waste Fire	**73%**
Model 1A First Responders with Pocket Dosimetry	
Model 1A Q7_1 Calibration Variables	
First Responders starting population [433]*	
Communication Distance [2]**	
Movement speed increase if [myRT >= 3.7]^	73%~

4.1.1.3 Model 1A: Novel Findings

Following verification and calibration, survey data values for the statement "*I would feel safe working/performing my normal duties during this event*" were substituted for the myradiationtolerance variable in Model 1A using the calibrated values based on the WTW: "*I would go to work if my employer requested it, even if it* *was not required"* survey statement response values. With this substitution, the percentage of first responders entering the radioactive contamination area markedly decreased from 70% to 3.7% with the Q6 dirty bomb scenario and from 73% to 5.5% for the Q7 radioactive plume scenario as shown in Figure 8A. This may be interpreted to mean that if estimates of first responders' personal comfort level in responding to an emergency with radioactive contamination is the only factor considered, that WTW may be dramatically lower.

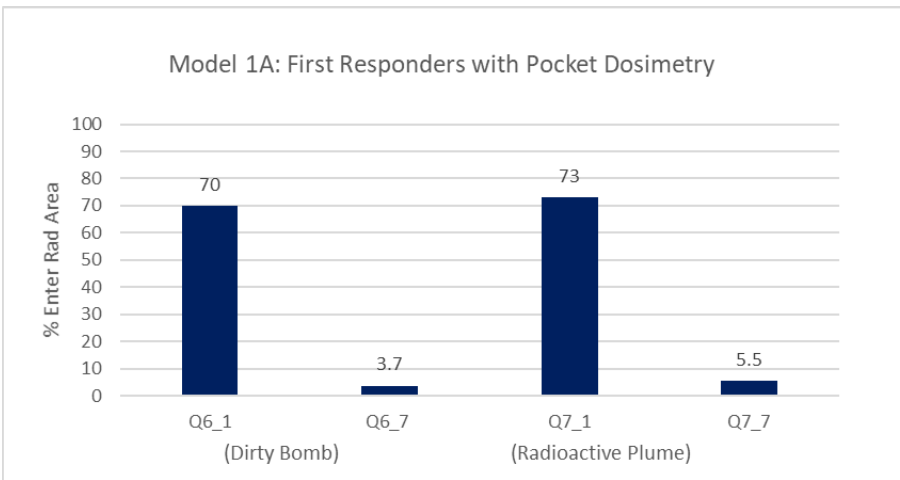
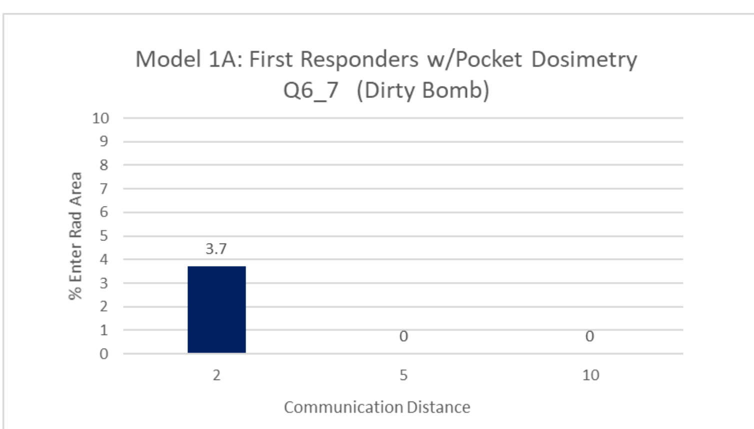


Figure 8. Model 1A: First Responders with Pocket Dosimetry <u>Novel Findings</u>

Data represents mean value from 50 runs of the number of first responder agents willing to enter an area with radioactive contamination. Q6_1 and Q7_1 represents percentage of first responder agents entering the area of radioactive contamination in the calibrated model using external dataset survey values for *"I would go to work if my employer requested it, even if it was not required"* survey statement for Q6 (dirty bomb) or Q7 (plume from radioactive waste fire) scenarios for the myradiationtolerance variable. Q6_7 and Q7_7 represent the percentage of first responder agents entering the area of radioactive contamination in the model using external data set survey values for *"I would feel safe working/performing my normal duties during this event"* for the myradiationtolerance variable. This includes a starting first responder population [433].

Following this direct comparison of the survey data for *"I would feel safe working/performing my normal duties during this event"* and its effect on output in Model 1A using the calibrated settings we sought to examine the effect of changes to the communication variable. Figure 9 A) (Q6 dirty bomb) and B) (Q7 plume from radioactive waste fire) shows the effect of communication distance on percentage of first responders entering the radioactive contamination area. If all other variables are held constant and only communication is changed, as communication distance widens the group myradiationtolerance variable average which drives speed, may be decreased depending on the preexisting myradiationtolerance population distribution. In this dataset, this reduced the percentage of first responder agents entering the radioactive contamination area.

A)



B)

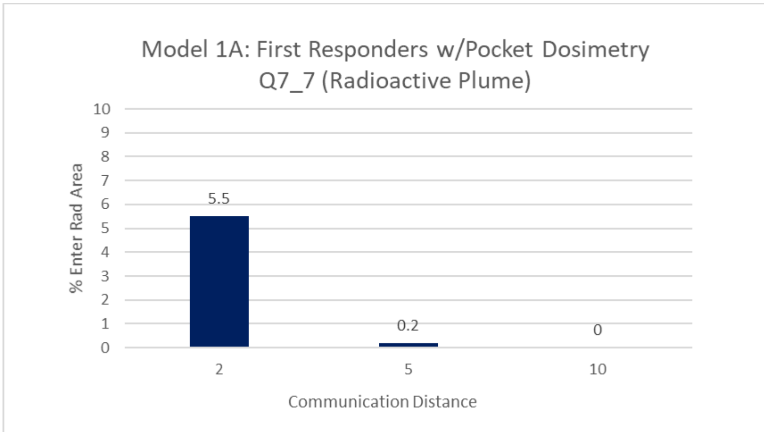


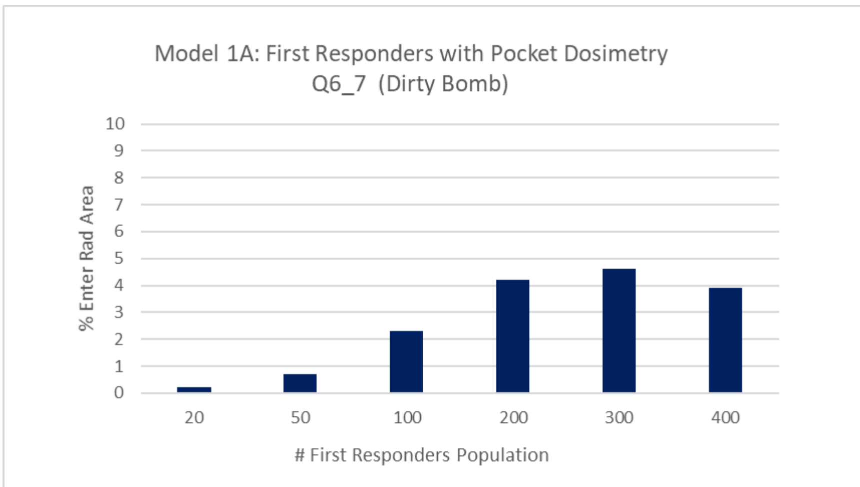
Figure 9. Model 1A: First Responders with Pocket Dosimetry Novel Findings

Data represents mean value from 50 runs of the number of first responder agents willing to enter an area with radioactive contamination. A) Q6_7 (dirty bomb) and B) Q7_7 (plume from radioactive waste fire) represent the percentage of first responder agents entering the area of radioactive contamination in the model using external data set survey values for *"I would feel safe working/performing my normal duties during this event"* for the myradiationtolerance variable. Communication distance represents the distance (patches) over which agents can communicate their respective myradiationtolerance variable information. This includes a starting first responder population [433].

I also examined if communication [2] is held constant, the effect of starting population size on the final percentage of first responder agents entering the radioactive contamination area. In Figure 10 A) (dirty bomb) and B) (plume from radioactive waste fire) I found a direct correlation between starting population size and percentage of agents entering the radioactive contamination area at population sizes ≤

[200]. Starting population sizes ≥ [200] had no effect on the final percentage of first responder agents willing to enter the radioactive contamination area.

A)



B)

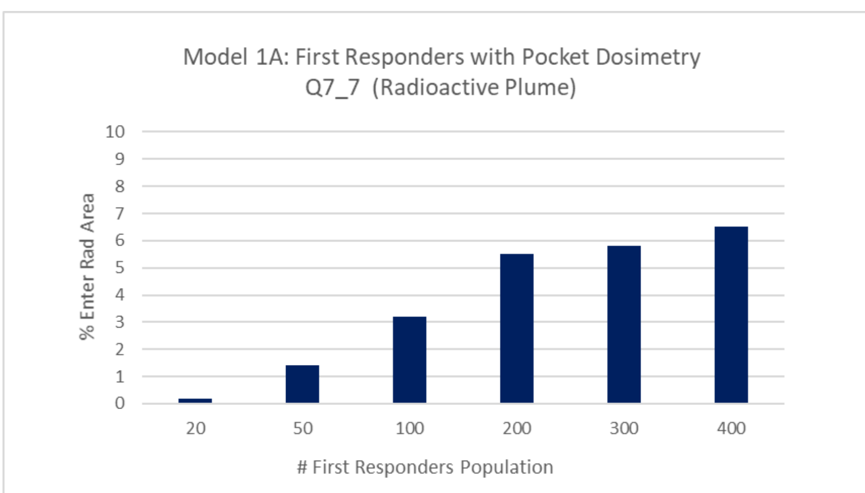
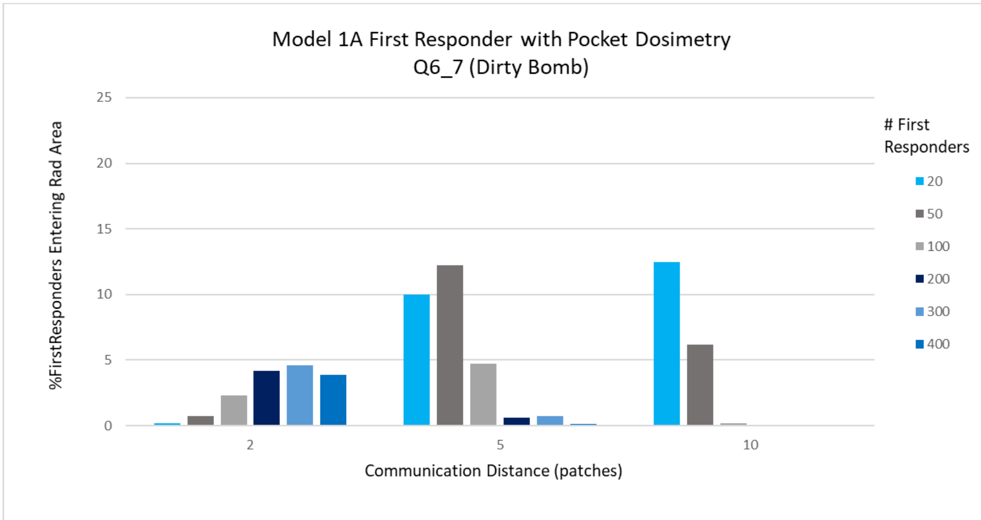


Figure 10. Model 1A: First Responders with Pocket Dosimetry <u>Novel Findings</u>

Data represents mean value from 50 runs of the number of first responder agents willing to enter an area with radioactive contamination. A) Q6_7 (dirty bomb) or B) Q7_7 (plume from radioactive waste fire) represents the percentage of first responder agents entering the area of radioactive contamination in the model using external data set survey values for *"I would feel safe working/performing my normal duties during this event"* for the myradiationtolerance variable. A communication distance of [2] patches was held constant and represents the distance (patches) over which agents can communicate their respective myradiationtolerance variable information. This series includes a variable starting first responder population of [20], [50[, [100], [200], [300] and [400] respectively.

Finally, I examined outcomes in the calibrated model when neither the first responder starting population, nor the communication variables were held constant. As shown in Figure 11 A) (dirty bomb) and B) (plume from radioactive waste fire), the percentage of first responders entering the radioactive contamination area increases as the starting population size increases at communication [2], but decreases as population size increases with communication distances ≥ [5]. This is explained as the greater the communication distance the greater the number of neighbors of the myradiationtolerance average which lowers the average and in turn lowers the speed of the agents. It is also worth noting that in this model, the percentage of first responders entering the radioactive contamination area never increases above 20%.

A)



B)

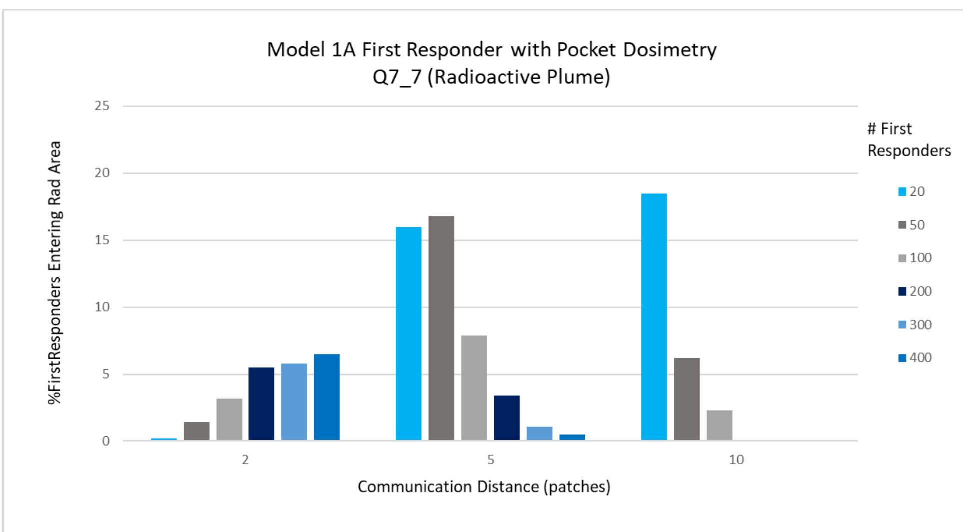


Figure 11. Model 1A: First Responders with Pocket Dosimetry <u>Novel Findings</u>

Data represents mean value from 50 runs of the number of first responder agents willing to enter an area with radioactive contamination. A) Q6_7 (dirty bomb) and B) Q7_7 (plume from radioactive waste fire) represents the percentage of first responder agents entering the area of radioactive contamination in the model using external data set survey values for *"I would feel safe working/performing my normal duties during this event"* for the myradiationtolerance variable. For this series, communication distance, which represents the distance (patches) over which agents can communicate their respective myradiationtolerance variable information was varied at [2], [5] and [10]. This series also included a variable starting first responder population of [20], [50], [100], [200], [300] and [400] respectively.

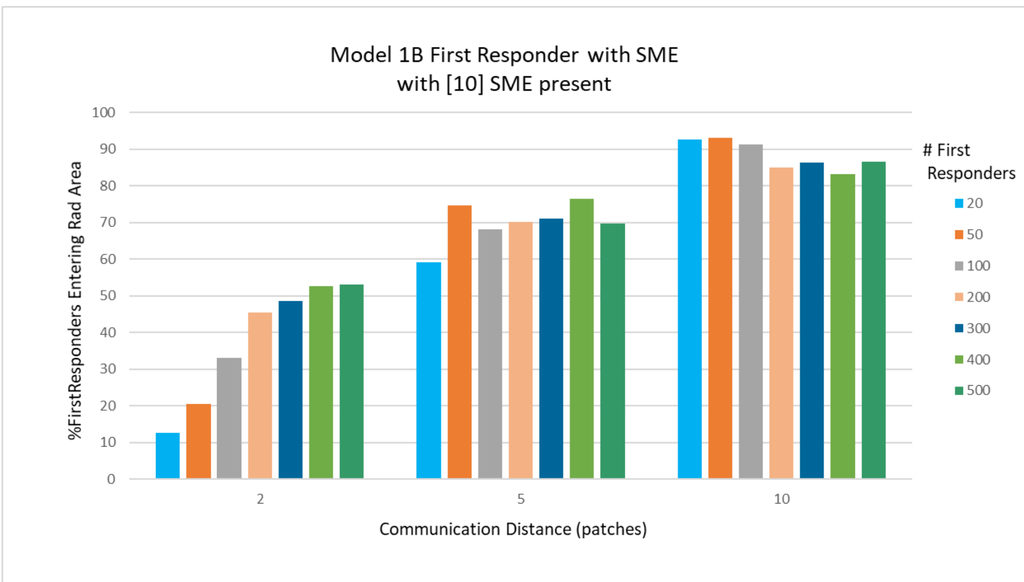
4.1.2 Model 1B: First Responders with Presence of Radiation Subject Matter Experts

4.1.2.1 Model 1B: Verification

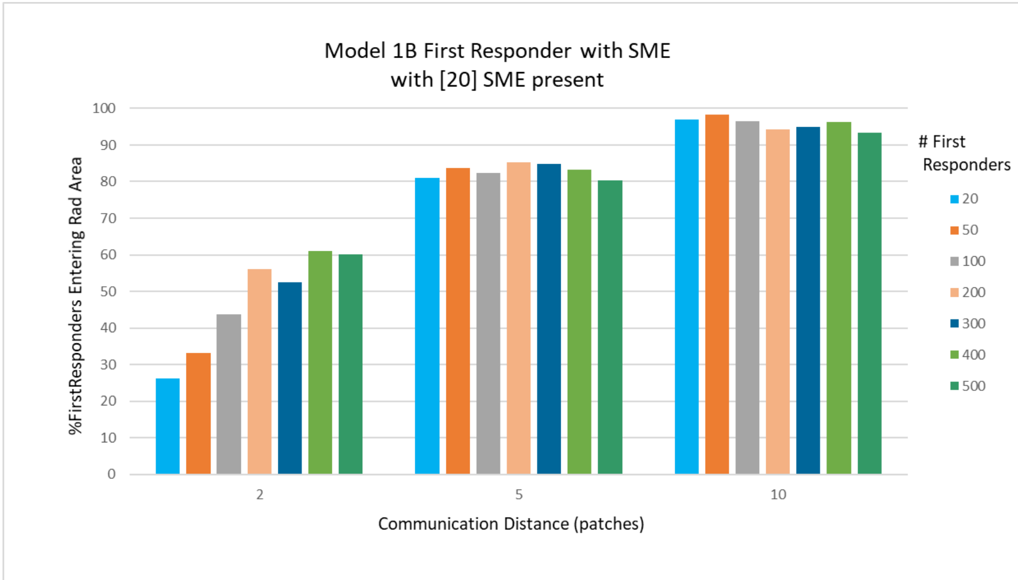
For verification of Model 1B, a range of values was explored for each key variable in the model including the size of the starting population of first responders, the size of the starting population of radiation SME, the range of communication distance (patches) with which the agents can exchange information. In the verification phase first responder agents were assigned a myradiationtolerance value using a normal distribution in the same numerical range as the external dataset survey values. As shown in Figure 12, the model is performing as expected under a wide range of values. We see a positive correlation between the percentage of first responders entering the radioactive contamination area with increasing communication and with increasing number of SME. This trend is generally proportional of the population size at a communication of [2] patches. At communication distance of [5] patches, there is no significant trend with starting populations over [100] on the percentage of first responders entering the radioactive contamination area. At a communication distance of [10] patches there is no significant trend of percentage of first responders entering the radioactive contamination area with respect to starting population size.

Additionally, I saw an overall increase in percentage of first responders entering the radioactive contamination area irrespective of population size or communication distance with increasing number of SME. I also saw that increasing the number of SME had more population driven effect at lower communication distances.

A)



B)



C)

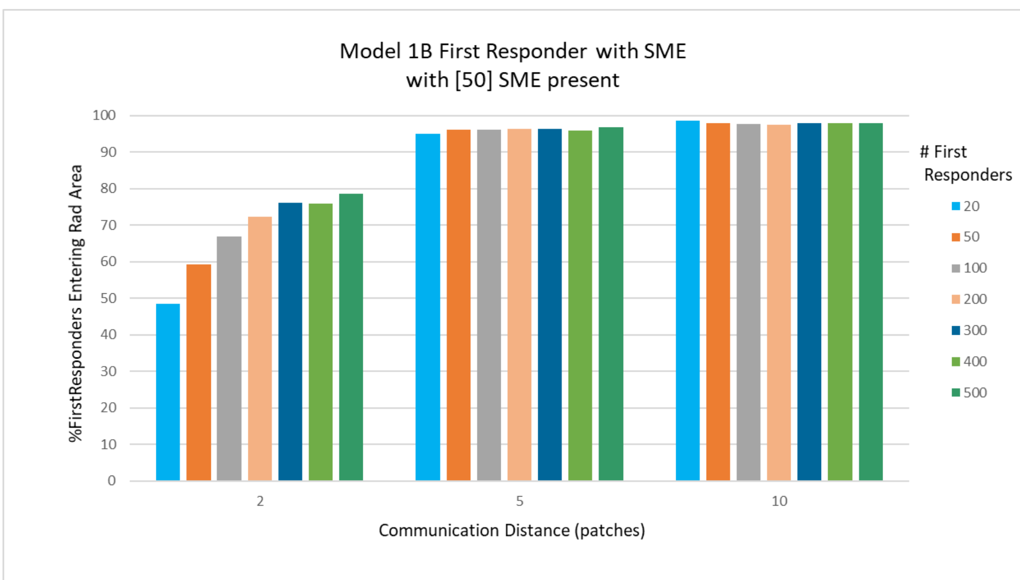


Figure 12. Model 1B: First Responders with Presence of Radiation Subject Matter Experts <u>Model Verification</u>

Data represents mean value from 20 runs. Communication distance represents the distance in (patches) over which agents can communicate their respective myradiationtolerance variable information. The number of first responders refers to the starting population size of "first responder" agents in the model.

For this series of figures, an additional A) [10], B) [20] or C) [50] radiation SMEs were added to the starting agent population.

4.1.2.2 Model 1B: Calibration

For calibration of Model 1B, an external data set sourced from the Turner et. al study, which includes survey responses to a series of statements regarding first responders' willingness to work during two scenarios where radioactive contamination is present was used (3). The Q6 scenario involved emergency response to a dirty bomb event and the Q7 scenario involved emergency response to a radioactive waste fire with an aerosolized radioactive plume. From this survey dataset, participant scores for the statement *"I would go to work if my employer requested it, even if it was not required"* translated as "willingness to work" (WTW) were substituted in the model for values for the myradiationtolerance variable and model variables for speed were calibrated so that the percentage of first responders entering the radioactive contamination area in the model matched the reported willingness to work percentages reported in the survey. This was completed for both the Q6 and Q7 scenarios with communication [2] and a starting first responder population in the model of [433] to match the number [433] of survey respondents. As shown in Table 5, Model 1B for the Q6 scenario, the survey data reported a 68.4% WTW and the model was calibrated to 70% first responder agents entering the radioactive contamination area. For Model 1B for the Q7 scenario, the survey data reported a 73% WTW and the model was calibrated to 74% first responder agents entering the radioactive contamination area. (Table 5)

Table 5. Model 1B: First Responders with Presence of Radiation Subject Matter Experts Model Calibration

[*]the number of agents populated in the model, 433 directly correlates with the # of survey respondents

[&]the number of radiation subject matter experts [10] present in the model

[**]patch distance over which the agents can communicate and share their respective mineradiationtolerance values

[^]myRT is the average of myradiationtolerance of close neighbors

[~]final model calibration WTW % represent the mean of 40 runs

Model Calibration with External Data Set: First Responder Survey Data	
Model Calibration to Survey Question:	**WTW**
Q6_1 WTW in Dirty Bomb Scenario	**68.4%**
Model 1B First Responders with Presence of Radiation Subject Matter Experts	
Model 1B Q6_1 Calibration Variables	
First Responders starting population [433]*	
SME starting population [10]&	
Communication Distance [2]**	
Movement speed increase if [myRT >= 3.65]^	70%~
Model Calibration to Survey Question:	**WTW**
Q7_1 WTW in Radioactive Plume from Radioactive Waste Fire	**73%**
Model 1B First Responders with Presence of Radiation Subject Matter Experts	
Model 1B Q7_1 Calibration Variables	
First Responders starting population [433]*	
SME starting population [10]&	
Communication Distance [2]**	
Movement speed increase if [myRT >= 3.75]^	74%~

4.1.2.3 Model 1B: First Responders with Presence of Radiation Subject Matter Experts

Novel Findings

Following verification and calibration, survey data values for the statement "*I would feel safe working/performing my normal duties during this event*" were substituted for the myradiationtolerance variable in Model 1B using the calibrated values based on the WTW: *"I would go to work if my employer requested it, even if it was not required"* survey statement response values. With this substitution, the percentage of first responders entering the radioactive contamination area markedly decreased from 70% to 4.9% with the Q6 dirty bomb scenario and from 74% to 7.4% for the Q7 radioactive plume scenario as shown in Figure 13. This may be interpreted to mean that if estimates of first responders' personal comfort level in responding to an emergency with radioactive contamination is the only factor considered, that WTW may be dramatically lower.

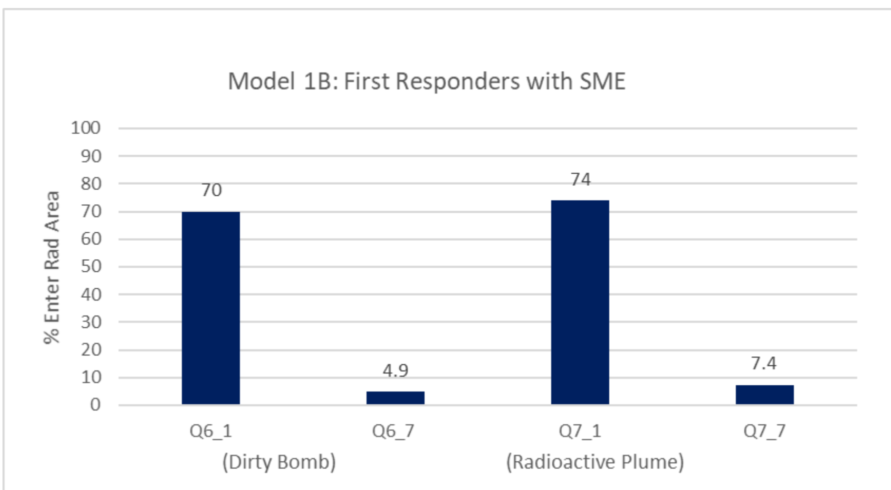
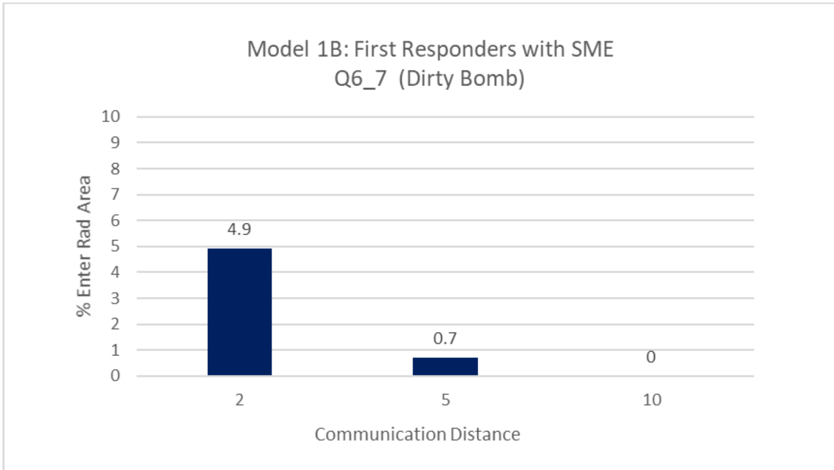


Figure 13. Model 1B: First Responders with Presence of Radiation Subject Matter Experts <u>Novel Findings</u>

Data represents mean value from 50 runs of the number of first responder agents willing to enter an area with radioactive contamination. Q6_1 and Q7_1 represents the percentage of first responder agents entering the area of radioactive contamination in the calibrated model using external dataset survey values for *"I would go to work if my employer requested it, even if it was not required"* survey statement for Q6 (dirty bomb) or Q7 (plume from radioactive waste fire) scenarios for the myradiationtolerance variable. Q6_7 and Q7_7 represent the percentage of first responder agents entering the area of radioactive contamination in the model using external data set survey values for *"I would feel safe* *working/performing my normal duties during this event"* for the myradiationtolerance variable. This includes a starting first responder population [433] and SME population of [10].

Following this direct comparison of the survey data for *"I would feel safe working/performing my normal duties during this event"* and its effect on output in Model 1B using the calibrated settings I sought to examine the effect of changes to the communication variable. Figure 14 A) (Q6 dirty bomb) and B) (Q7 plume from radioactive waste fire) shows the effect of communication distance on percentage of first responders entering the radioactive contamination area. If all other variables are held constant and only communication is changed, as communication distance widens the group myradiationtolerance variable average which drives speed, may be decreased depending on the preexisting myradiationtolerance population distribution. In this dataset, this reduces the percentage of first responder agents entering the radioactive contamination area. This trend is highly similar to what was observed in Model 1A (Figure 9), though with the addition of SME in Model 1B (Figure 14) the overall values are higher. For example, at a communication distance of [2], Figure 9 shows a percentage of 3.7% and 5.5% for the Q6 and Q7 scenarios respectively and in Figure 14 a percentage of 4.9% and 7.4% for the Q6 and Q7 scenarios respectively.

A)



B)

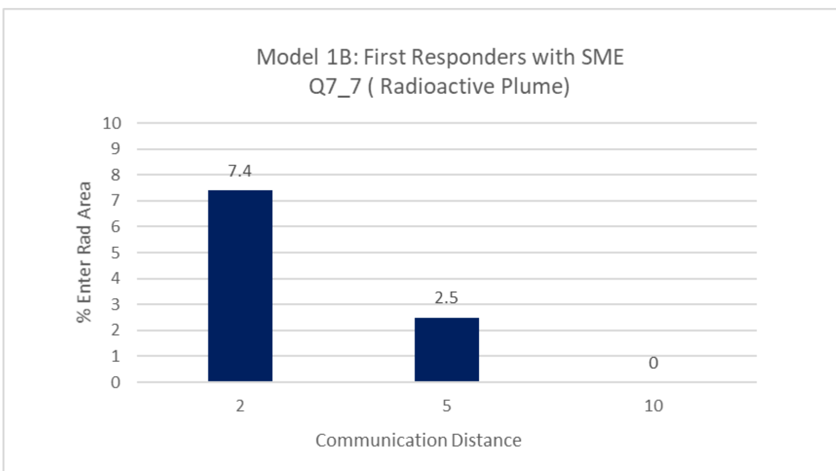
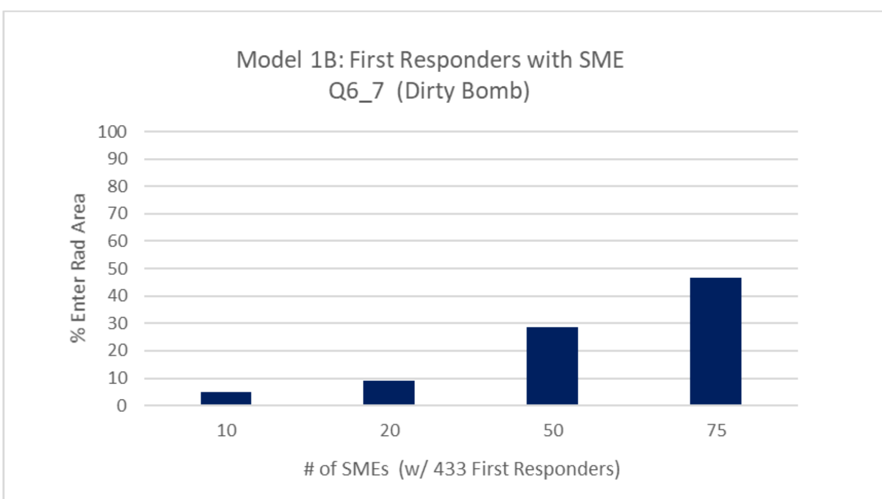


Figure 14. Model 1B: First Responders with Presence of Radiation Subject Matter Experts <u>Novel Findings</u>

Data represents mean value from 50 runs of the number of first responder agents willing to enter an area with radioactive contamination. A) Q6_7 (dirty bomb) and B) Q7_7 (plume from radioactive waste fire) represents the percentage of first responder agents entering the area of radioactive contamination in the model using external data set survey values for *"I would feel safe working/performing my normal duties during this event"* for the myradiationtolerance variable. Communication distance represents the distance in patches over which agents can communicate their respective myradiationtolerance variable information. This includes a starting first responder population [433] and SME population of [10].

I also examined if communication [2] is held constant, the effect of starting population size of SME on the final percentage of first responder agents entering the radioactive contamination area. In Figure 15 A) (dirty bomb) and B) (plume from radioactive waste fire) I found a direct correlation between starting population size of SME and percentage of agents entering the radioactive contamination area at a first responder population size [433].

A)



B)

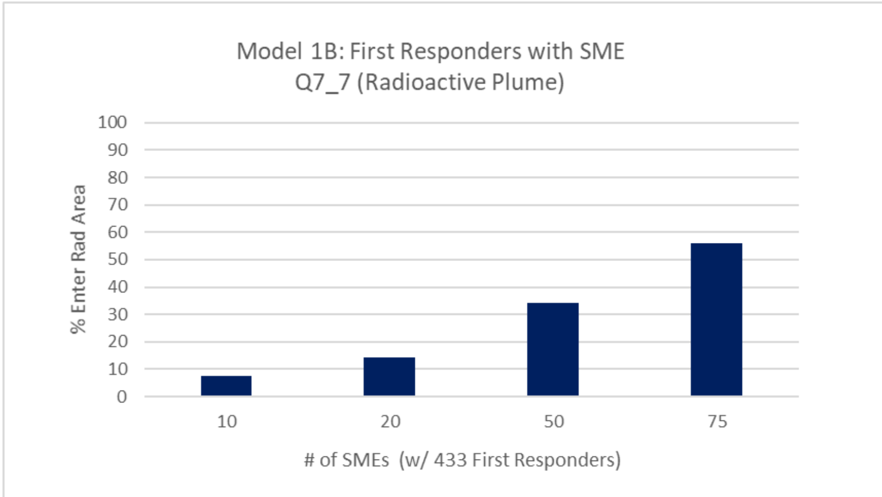
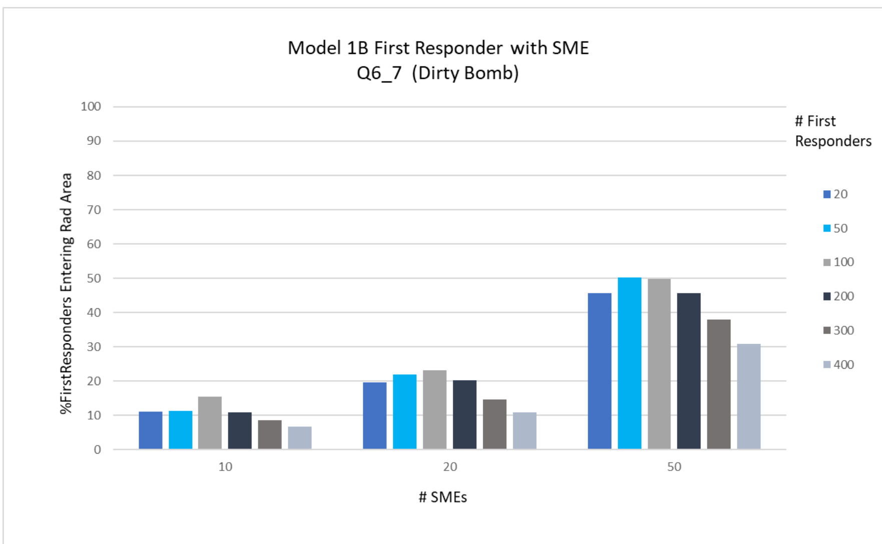


Figure 15. Model 1B: First Responders with Presence of Radiation Subject Matter Experts Novel Findings

Data represents mean value from 50 runs of the number of first responder agents willing to enter an area with radioactive contamination. A) Q6_7 (dirty bomb) and B) Q7_7 (plume from radioactive waste fire) represent the percentage of first responder agents entering the area of radioactive contamination in the model using external data set survey values for *"I would feel safe working/performing my normal duties during this event"* for the myradiationtolerance variable. A communication distance of [2] patches was held constant and represents the distance (patches) over which agents can communicate their respective myradiationtolerance variable information. This series includes a starting first responder population [433] and a variable SME starting population of [10], [20], [50] and [75] respectively.

Similarly, I examined if communication [2] is held constant, the effect of starting population size of SME and starting population size of first responders on the final percentage of first responder agents entering the radioactive contamination area. In Figure 16 A) (dirty bomb) and B) (plume from radioactive waste fire) I found at SME [20] and [50] and first responder population $\leq$ [100] a proportional increase in number of SME and percentage of first responders entering the radioactive contamination area, but at all SME starting population values a decreasing trend in percentage of first responders entering the radioactive contamination area as the starting first responder population size increases ≥ [200]. This correlates with a ratio effect, i.e. as the number of SME is held constant and first responder population increases the proportional ratio of SME: first responders decreases.

A)



B)

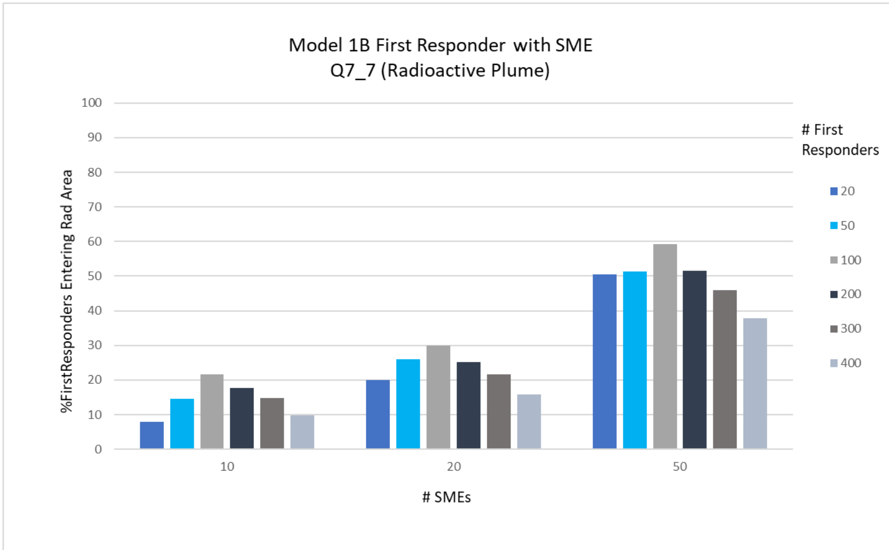
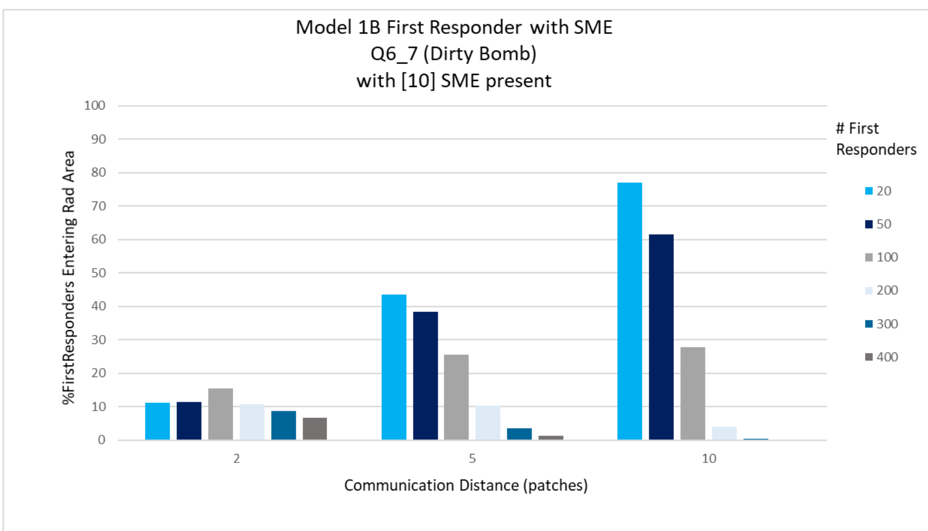


Figure 16. Model 1B: First Responders with Presence of Radiation Subject Matter Experts <u>Novel Findings</u>

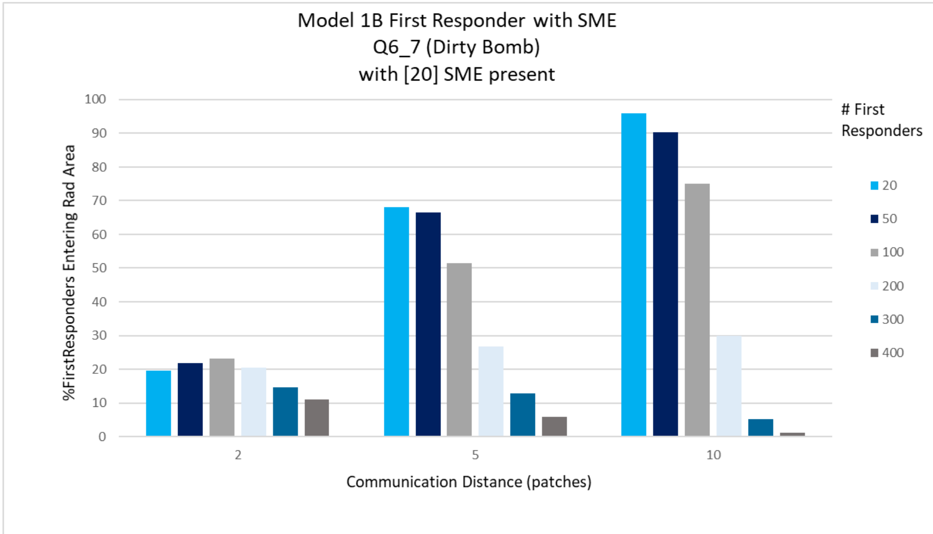
Data represents mean value from 50 runs of the number of first responder agents willing to enter an area with radioactive contamination. A) Q6_7 (dirty bomb) and B) (plume from radioactive waste fire) represent the percentage% of first responder agents entering the area of radioactive contamination in the model using external data set survey values for *"I would feel safe working/performing my normal duties during this event"* for the myradiationtolerance variable. For this series, communication distance [2] which represents the distance (patches) over which agents can communicate their respective myradiationtolerance variable information was held constant. This series also included a variable starting first responder population of [20], [50], [100], [200], [300] and [400] and a variable SME starting population of [10], [20] and [50] respectively.

Finally, I examined outcomes in the calibrated model when neither the first responder starting population, the SME population or the communication variables were held constant. As shown in Figure 17 A)-C) for the dirty bomb scenario, and D)- F) for the plume from radioactive waste fire scenario, the percentage of first responders entering radioactive contamination area is affected by the ratio of SME to the respective starting first responder population and concurrently by the communication distance. If the SME ratio is low then as communication increases the percentage of first responders decreases, if the SME ratio is high then as communication increases so does percentage of first responders. These trends were consistent for both the Q6_7 Dirty bomb and Q7_7 plume from radioactive waste fire scenarios. In this model series which included the presence of SME, at certain variable value combinations, the percentage of first responders entering the radioactive contamination area approached 100%.

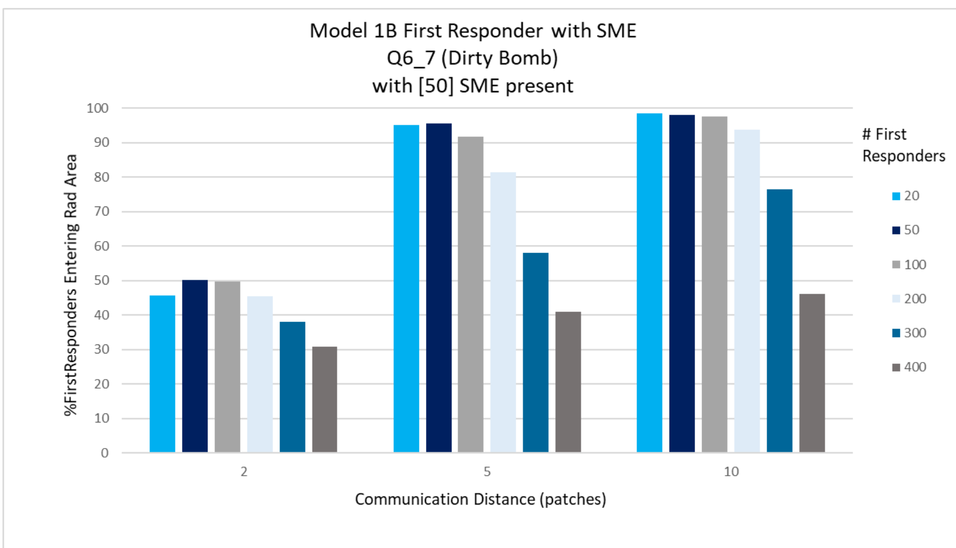
A)



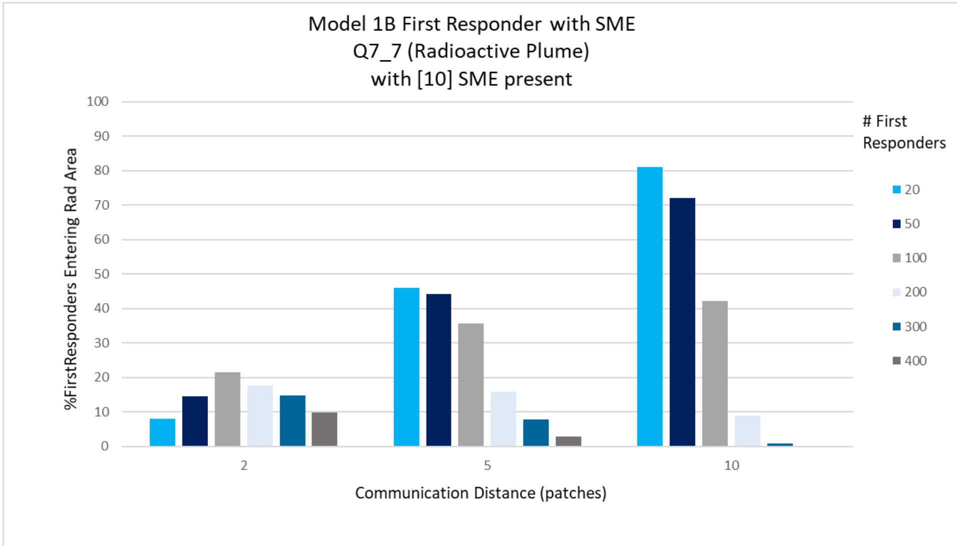
B)


Model 1B First Responder with SME
Q6_7 (Dirty Bomb)
with [20] SME present
%FirstResponders Entering Rad Area
Communication Distance (patches)
First
Responders
20
50
100
200
300
400
0
10
20
30
40
50
60
70
80
90
100
2
5
10

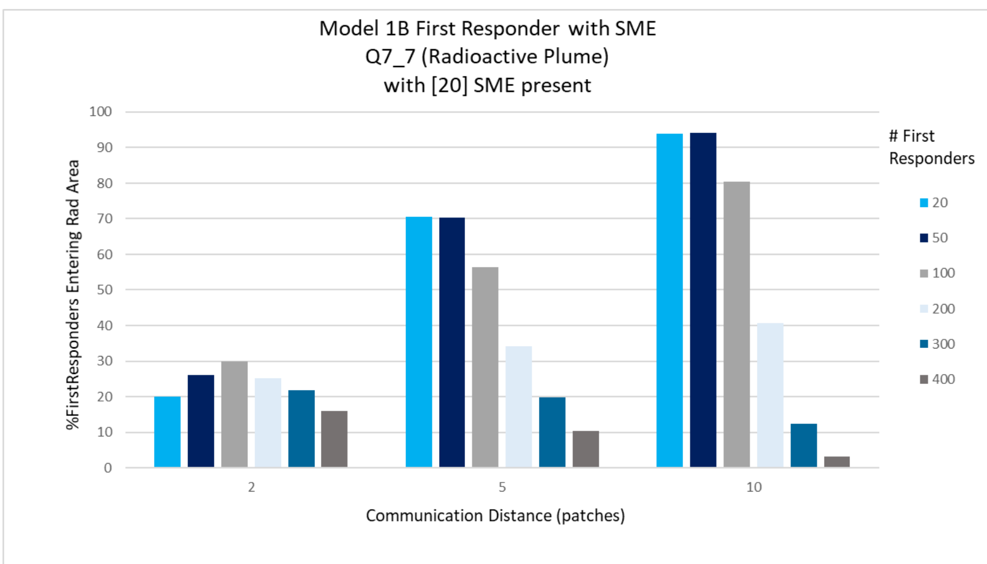
C)


Model 1B First Responder with SME
Q6_7 (Dirty Bomb)
with [50] SME present
%FirstResponders Entering Rad Area
Communication Distance (patches)
First
Responders
20
50
100
200
300
400
0
10
20
30
40
50
60
70
80
90
100
2
5
10

D)


Model 1B First Responder with SME
Q7_7 (Radioactive Plume)
with [10] SME present
%FirstResponders Entering Rad Area
100
90
80
70
60
50
40
30
20
10
0
2
5
10
Communication Distance (patches)
First
Responders
20
50
100
200
300
400

E)


Model 1B First Responder with SME
Q7_7 (Radioactive Plume)
with [20] SME present
%FirstResponders Entering Rad Area
100
90
80
70
60
50
40
30
20
10
0
2
5
10
Communication Distance (patches)
First
Responders
20
50
100
200
300
400

F)

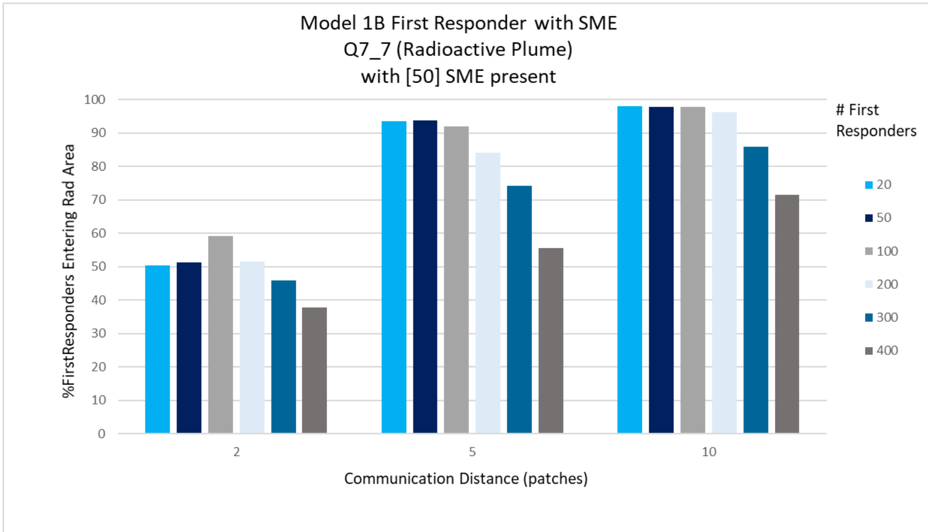


Figure 17. Model 1B: First Responders with Presence of Radiation Subject Matter Experts Novel Findings

Data represents mean value from 50 runs of the number of first responder agents willing to enter an area with radioactive contamination. Q6_7 (dirty bomb) for A) SME [10], B) SME [20], C) SME [50] and for Q7_7 (plume from radioactive waste fire) for D) SME [10] E) SME [20] and F) [50] represent the percentage of first responder agents entering the area of radioactive contamination in the model using external data set survey values for *"I would feel safe working/performing my normal duties during this event"* for the myradiationtolerance variable. For this series, a communication distance which represents the distance (patches) over which agents can communicate their respective myradiationtolerance variable information of [2], [5] and [10] was used.

4.2 Model 2 Series: First Responders Willingness to Triage Patients with Radioactive Contamination

This computational model series is designed to explore factors which affect first responders' willingness to render medical treatment and triage to patients who may be contaminated with radioactive contamination. In Model 2A: Triage with Pocket Dosimetry an agent population consisting only of civilians and first responders is generated. In Model 2B: Triage with SME, an agent population consisting of civilians, first responders and additional radiation SME are generated. Each model was constructed and evaluated through a testing phase or *verification phase*, to verify that the model algorithms were performing appropriately, a *calibration phase* where the model settings were fine-tuned using the external survey data set and a *novel findings* phase, where novel data were generated based on the established reference settings from the calibration phase. The primary output of both models is measured in the percentage of first responders willing to triage patients who may be contaminated with radioactive material. A secondary output of both models includes the percentage of civilians who have been triaged.

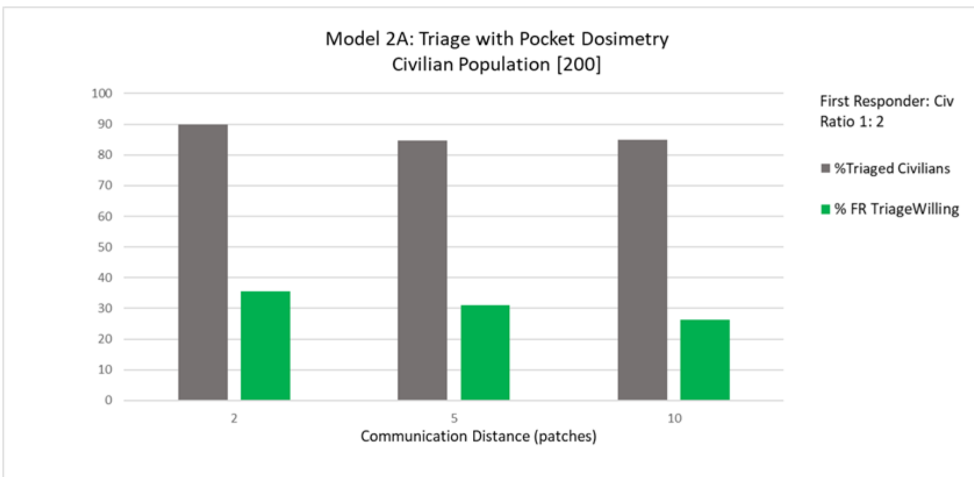
4.2.1 Model 2A: Triage with Pocket Dosimetry

4.2.1.1 Model 2A: Verification

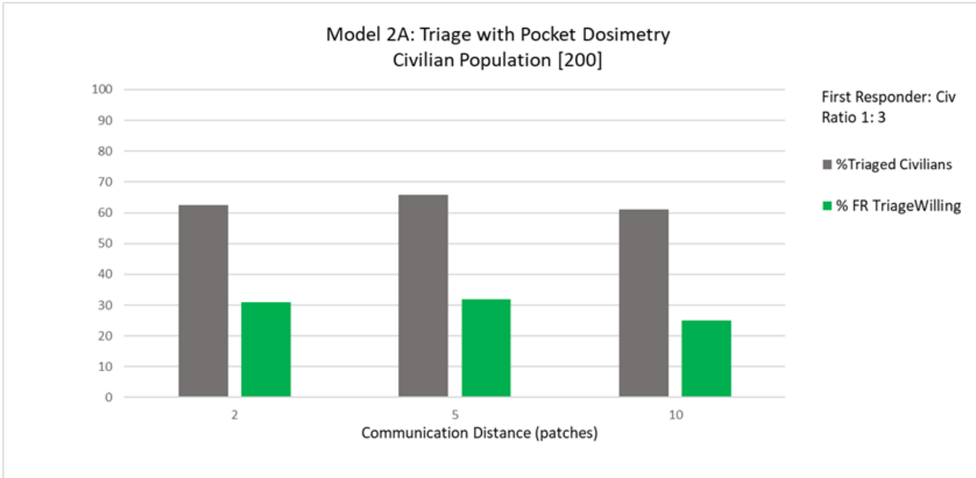
For verification of Model 2A: Triage with Pocket Dosimetry, a range of values was explored for each key variable in the model including the size of the starting population of first responders, the size of the starting population of civilians, and the range of communication distance (patches) with which the agents can exchange information. In the verification phase first responder agents were assigned a myradiationtolerance value using a normal distribution in the same numerical range as the external dataset survey values. As shown in Figure 18 and Figure 19, the model is performing as expected under a wide range of values. Figure 18 includes data for a starting civilian population of [200] with first responder to civilian ratios of 1:2, 1:3, 1:5, and 1:10 in Figure 18 A)-D) respectively. Figure 19 includes data for the same series of first responder to civilian ratios in Figure 18 A)-D) but with a larger starting population of [500] civilians. Across both series, a general inverse correlation between percentage of first responders willing to triage and communication (patch distance) was seen. As communication increased the percentage of first responders willing to triage decreased.

This is most clearly seen with the higher first responder to civilian ratios of 1:2 and 1:3 (Figure 18 A) and B) and Figure 19 A) and B). At lower first responder to civilian ratios of 1:5 and 1:10 (Figure 18 and 19: C) and D) respectively), this trend is less obvious reflecting that with less agents present in the model, the effect of communication distance is muted as there are less agents present in general with which to interact. This series also shows the effect of first responder to civilian ratio on percentage of civilians triaged. As shown in Figure series 18 and 19, there is a positive correlation between percentage of triaged civilians and higher first responder to civilian ratio. These data collectively demonstrate that the model is behaving consistently across a range of values. Also, consistent trends were found at two significantly different sized civilian agent populations [200] vs. [500] which supports the strength of the model algorithm.

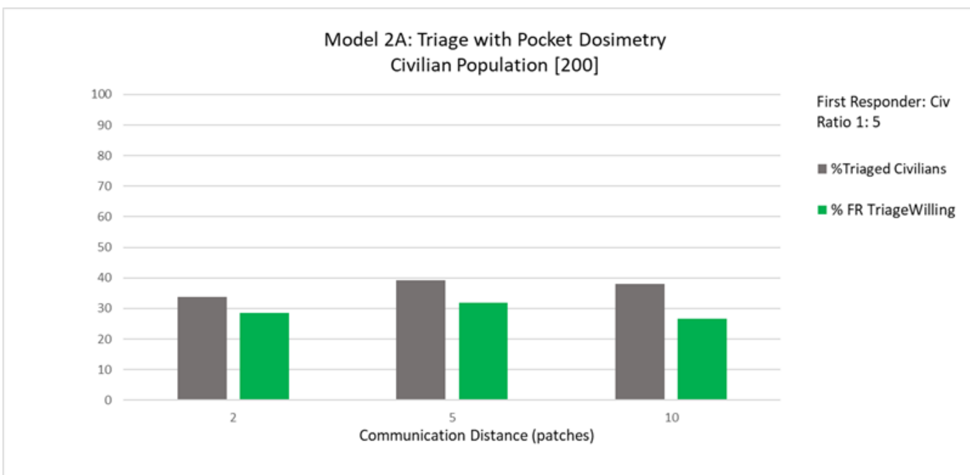
A)



B)


Model 2A: Triage with Pocket Dosimetry
Civilian Population [200]
First Responder: Civ
Ratio 1: 3
%Triaged Civilians
% FR TriageWilling
100
90
80
70
60
50
40
30
20
10
0
2
5
10
Communication Distance (patches)

C)


Model 2A: Triage with Pocket Dosimetry
Civilian Population [200]
First Responder: Civ
Ratio 1: 5
%Triaged Civilians
% FR TriageWilling
100
90
80
70
60
50
40
30
20
10
0
2
5
10
Communication Distance (patches)

D)

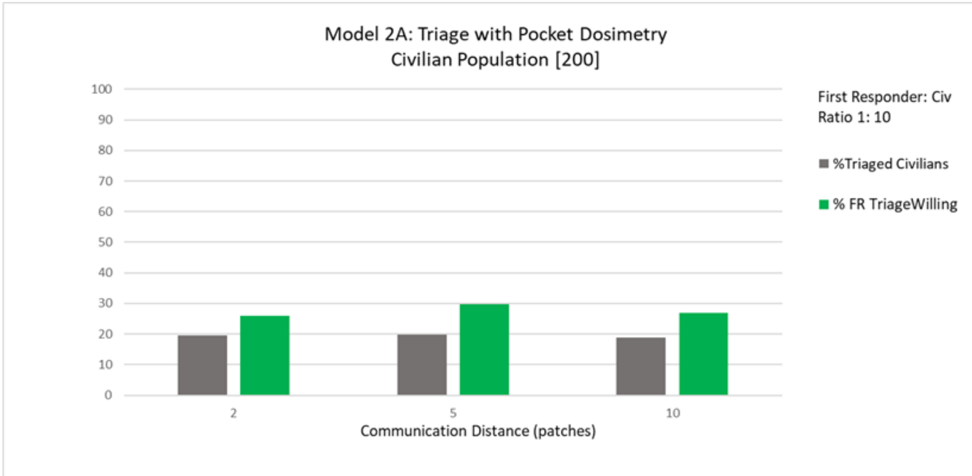
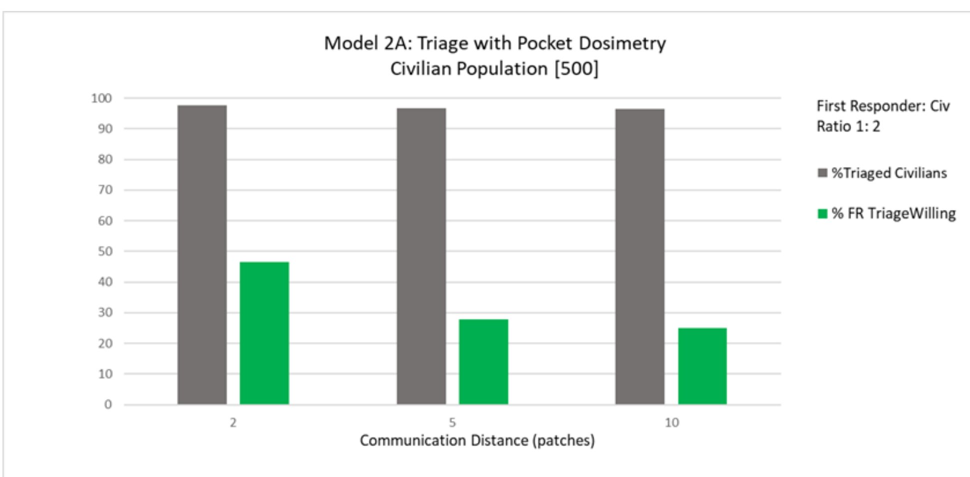


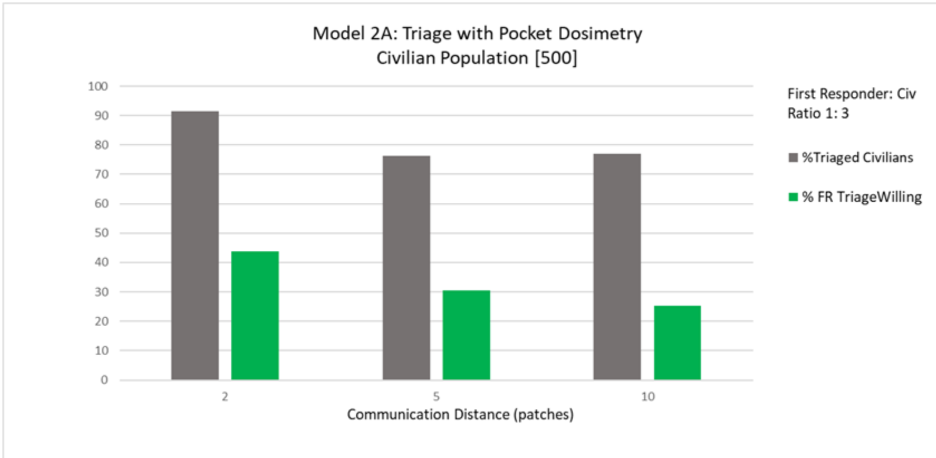
Figure 18. Model 2A: Triage with Pocket Dosimetry **<u>Model Verification</u>**

Data represents mean value from 10 runs. A civilian agent population size of [200] was used and respective ratios of 1:2, 1:3, 1:5 and 1:10 of first responder agents to civilian agents was included. Communication distance represents the distance (patches) over which agents can communicate their respective myradiationtolerance variable information.

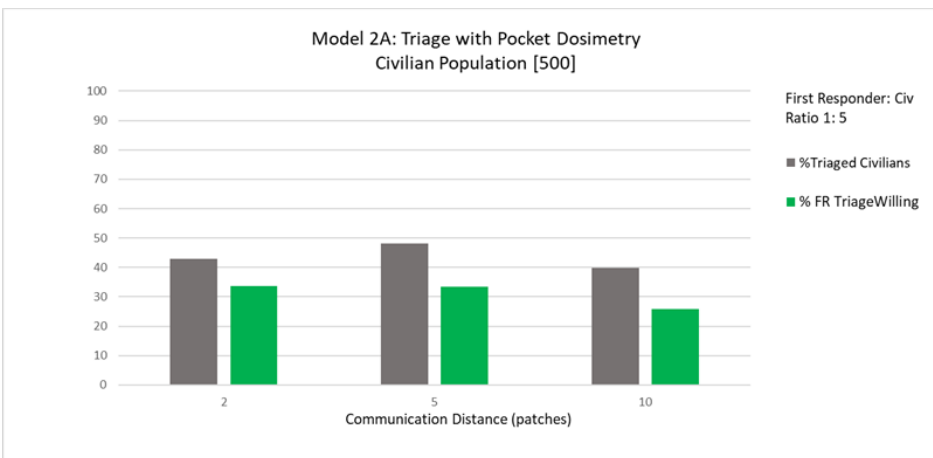
A)



B)


Model 2A: Triage with Pocket Dosimetry
Civilian Population [500]
100
90
80
70
60
50
40
30
20
10
0
2
5
10
Communication Distance (patches)
First Responder: Civ Ratio 1: 3
%Triaged Civilians
% FR TriageWilling

C)


Model 2A: Triage with Pocket Dosimetry
Civilian Population [500]
100
90
80
70
60
50
40
30
20
10
0
2
5
10
Communication Distance (patches)
First Responder: Civ Ratio 1: 5
%Triaged Civilians
% FR TriageWilling

D)

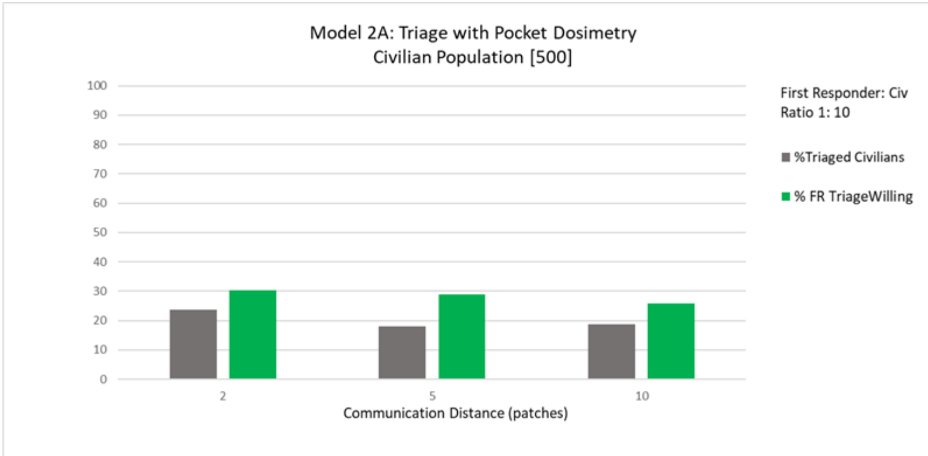


Figure 19. Model 2A: Triage with Pocket Dosimetry Model Verification

Data represents mean value from 10 runs. A civilian agent population size of [500] was used and respective ratios of 1:2, 1:3, 1:5 and 1:10 of first responder agents to civilian agents was included. Communication distance represents the distance (patches) over which agents can communicate their respective myradiationtolerance variable information.

4.2.1.2 Model 2A: Calibration

For calibration of Model 2A, an external data set sourced from the Turner et. al study, which includes survey responses to a series of statements regarding first responders' willingness to work during two scenarios where radioactive contamination is present was used (3). The Q6 scenario involved emergency response to a dirty Bomb event and the Q7 scenario involved emergency response to a radioactive waste fire with an aerosolized radioactive plume. From this survey dataset, participant scores for the statement *"I would go to work if my employer requested it, even if it was not required"* translated as "willingness to work" (WTW) were substituted in the model for values for the myradiationtolerance variable and model variables for communication were calibrated so that the percentage of first responders willing to triage patients with radioactive contamination matched the reported WTW percentages reported in the survey. This was completed for both the Q6 and Q7 scenarios with a starting first responder population in the model of [433] to match the number [433] of survey respondents and a starting civilian population of [500].

For this model series, the external data set values are directly applied to the agents so that the external data set WTW values should be translated explicitly in the model into "willingness to triage" values within the algorithm. As this model directly applies WTW values to the initial baseline myradiationtolerance distribution, the model was calibrated to communication [0]. As shown in Table 6, Model 2A for the Q6 scenario, the survey data reported a 68.4% WTW and the model was calibrated to 68.6% willingness to triage. For Model 2A for the Q7 scenario, the survey data reported a 73% WTW and the model was calibrated to 73.1% willingness to triage. Percentage of civilians triaged for the Q6 and Q7 scenarios were 100% and 99.9% respectively. With a civilian population of [500] and a first responder agent population of [433] to match the external data set values, this near 1:1 ratio of first responder to civilian is reflected in the near 100% triaged civilian values. (Table 6)

Table 6. Model 2A: Triage with Pocket Dosimetry <u>Model Calibration</u>

*the number of agents populated in the model 433, directly correlates with the number of survey respondents

**patch distance over which the agents can communicate and share their respective mineradiationtolerance values

^ a starting population of [500] civilian agents was held constant from the verification series

~ final model calibration WTW [triage-willing=true] percentage represent mean of 10 runs

Model Calibration with External Data Set: First Responder Survey Data	
Model Calibration to Survey Question:	**WTW**
Q6_1 WTW in Dirty Bomb Scenario	**68.4%**
Model 2A Triage with Pocket Dosimetry	
Model 2A Q6_1 Calibration Variables	
First Responders starting population [433]*	
Civilian starting population [500]^	
Communication Distance [0]**	
First Responoders with [triage-willing = true]	**68.6%~**
Civilians with [triaged = true]	**100%**
Model Calibration to Survey Question:	**WTW**
Q7_1 WTW in Radioactive Plume from Radioactive Waste Fire	**73%**
Model 2A Triage with Pocket Dosimetry	
Model 2A Q7_1 Calibration Variables	
First Responders starting population [433]*	
Civilian starting population [500]^	
Communication Distance [0]**	
First Responoders with [triage-willing = true]	**73.1%~**
Civilians with [triaged = true]	**99.9%**

4.2.1.3 Model 2A: Novel Findings

Following verification and calibration, survey data values for the statement "*I would feel safe working/performing my normal duties during this event*" were substituted for the myradiationtolerance variable in Model 2A using the calibrated values based on the WTW: "*I would go to work if my employer requested it, even if it was not required*" survey statement response values. With this substitution, the percentage of first responders willing to triage patients with radioactive contamination (triage willing) markedly decreased from 68.6% to 37.9% with the Q6 Dirty Bomb scenario and from 73.1% to 44.1% for the Q7 Radioactive plume scenario as shown in Figure 20. This is essentially a direct application of the external data set values to the agents myradiationtolerance. This may be interpreted to mean that if estimates of first responders' personal comfort level in providing medical treatment and triage to patients with radioactive contamination is the only factor considered, that WTW may be dramatically lower. Percentage of triaged civilians remains unaffected by percentage of triage-willing first responders as the model is flooded with a large first responder population at a ratio of approximately 1:1 with the civilian population

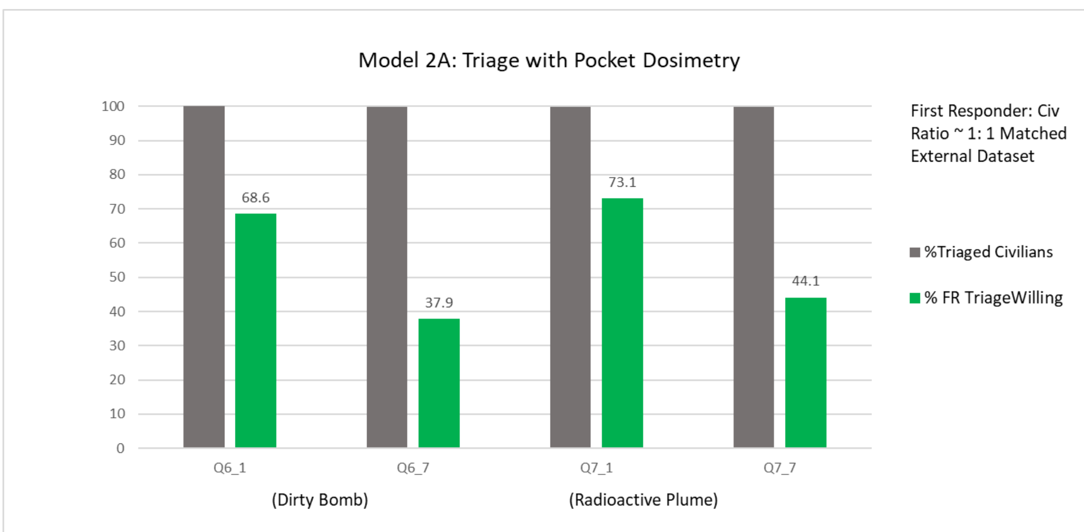


Figure 20. Model 2A: Triage with Pocket Dosimetry <u>Novel Findings</u>

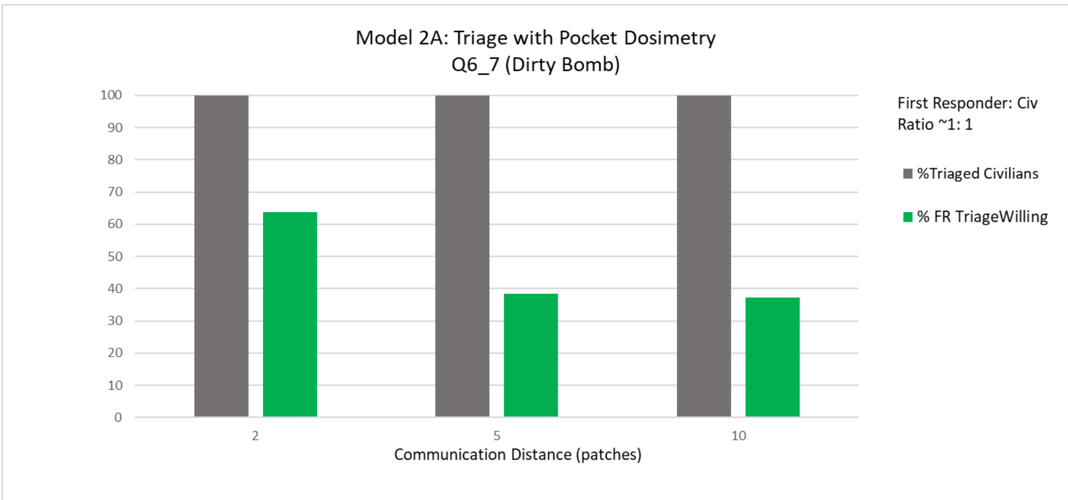
Data represents mean value from (n=10) runs of the percentage of first responder agents willing to triage patients with radioactive contamination (green) and the percentage of civilians triaged (gray). Q6_1 and

Q7_1 represents the percentage of first responder agents willing to triage patients with potential radioactive contamination in the calibrated model using external dataset survey values for *"I would go to work if my employer requested it, even if it was not required"* survey statement for Q6 (Dirty bomb) or Q7 (plume from radioactive waste fire) scenarios for the myradiationtolerance variable. Q6_7 and Q7_7 represent the percentage% of first responder agents willing to triage patients with potential radioactive contamination in the calibrated model using external data set survey values for *"I would feel safe working/performing my normal duties during this event"* for the myradiationtolerance variable. This includes a starting first responder population [433] and civilian population of [500].

Following this direct comparison of the survey data for *"I would feel safe working/performing my normal duties during this event"* and its effect on output in Model 2A using the calibrated settings, I sought to examine the effect of changes to the communication variable. Figure 21 A) (Q6 Dirty bomb) and B) (Q7 plume from radioactive waste fire) shows the effect of communication distance on percentage of first responders willing to triage patients with radioactive contamination.

If all other variables are held constant and only communication is changed, as communication distance widens more agents can communicate their myradiationtolerance and depending on the preexisting myradiationtolerance population distribution may negatively affect willingness to triage (as the mean mineradiationtolerance may be driven lower with a larger "n"). In this dataset, increasing communication reduces the percentage of first responder agents willing to triage patients with radioactive contamination as shown for both the Q6_7 (dirty bomb) and Q7_7 (plume from radioactive waste fire) scenarios in Figure 21 A) and B) respectively. The percentage of first responders willing to triage did not significantly affect the percentage of triaged civilians in this data series as the ratio of first responder to civilian was near 1:1.

A)



B)

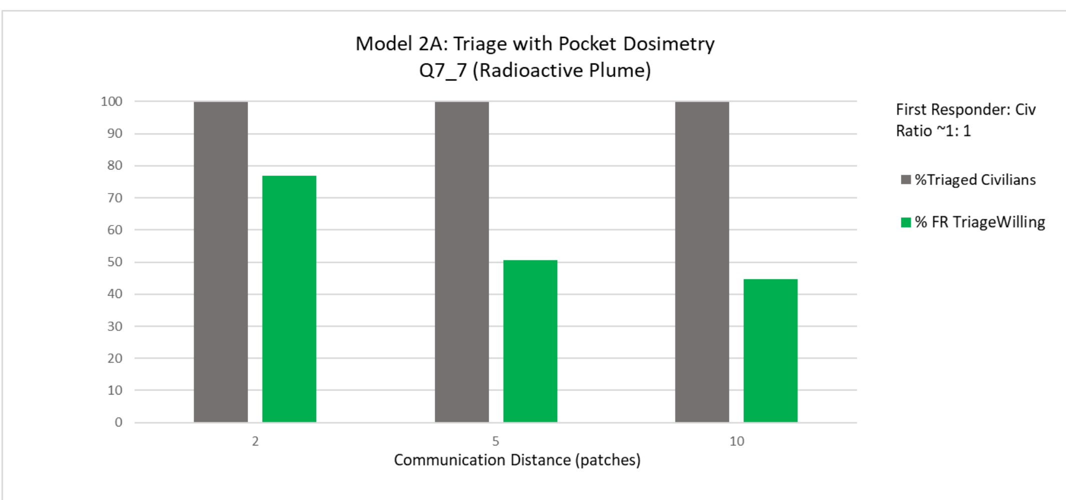
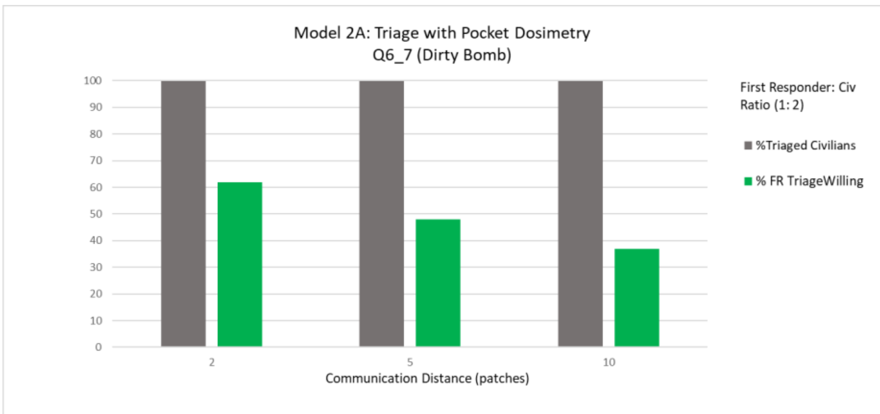


Figure 21. Model 2A: Triage with Pocket Dosimetry <u>Novel Findings</u>

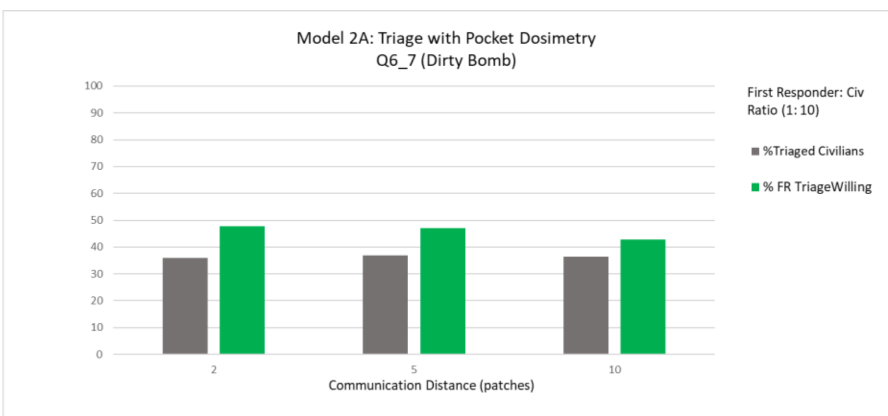
Data represents mean value from (n=10) runs of the percentage of first responder agents willing to triage patients with radioactive contamination (green) and the percentage of civilians triaged (gray). A) Q6_7 (Dirty bomb) and B) Q7_7 (plume from radioactive waste fire) represents the percentage of first responder agents willing to triage patients with radioactive contamination in the model using external data set survey values for *"I would feel safe working/performing my normal duties during this event"* for the myradiationtolerance variable. Communication distance represents the distance (patches) over which agents can communicate their respective myradiationtolerance variable information. This includes a starting first responder population [433] and civilian population of [500].

I also examined outcomes in the calibrated model with more realistic ratios of first responder to civilians in a mass casualty medical management situation. Ratios of first responders to civilians of 1:2 and 1:10 were modeled with variable communication distance. For both the Q6_7 (dirty bomb) and Q7_7 (plume from radioactive waste fire) scenarios in Figure 22 A) and C) with a first responder to civilian ratio of 1:2, the percentage of first responders willing to triage patients with radioactive contamination decreased with increasing communication distance. The effect of communication distance on first responder willingness to triage was not significant however, with a first responder to civilian ratio of 1:10 as shown in Figure 22 B) and D). Here, increasing communication had little effect on first responder willingness to triage as with a lower ratio of first responders to civilians there were less overall first responder agents in the model with which to interact. This series also shows the overall percentage of triaged civilians was higher with a higher first responder to civilian ratio of 1:2 as compared to 1:10, but also at ratios of 1:2 the large population of first responders precluded sensitivity to the downward trend of percentage of triage willing first responders as evidenced in Figure 22 A) and C).

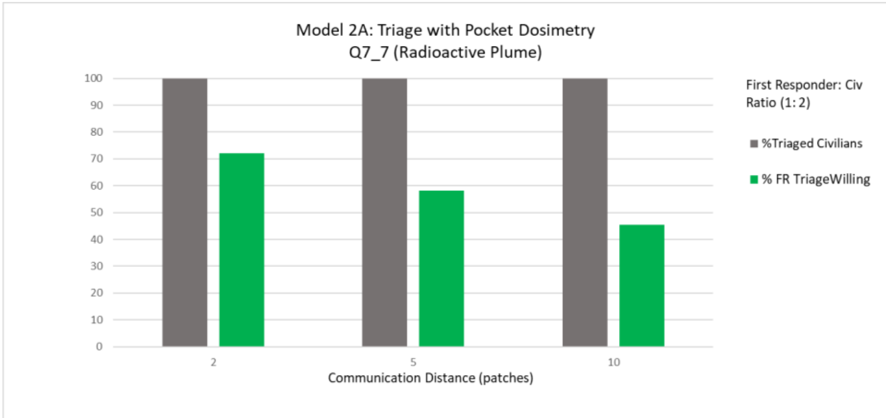
A)



B)



C)



D)

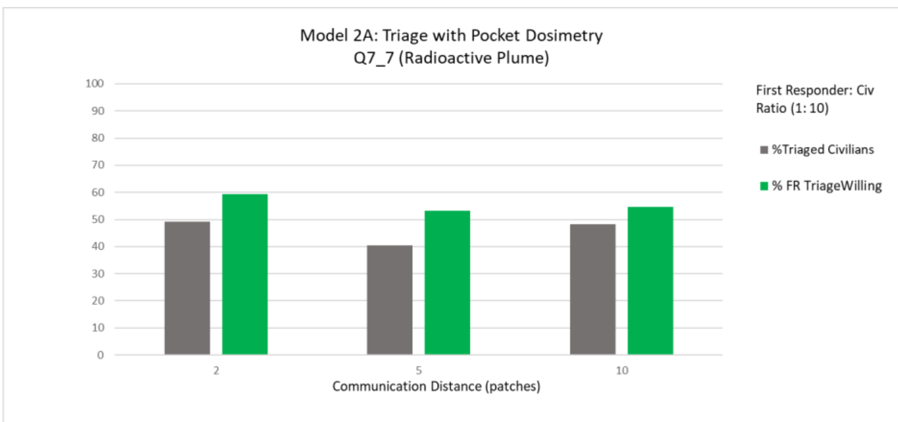


Figure 22. Model 2A: Triage with Pocket Dosimetry <u>Novel Findings</u>

Data represents mean value from (n=10) runs of the percentage of first responder agents willing to triage patients with radioactive contamination (green) and the percentage of civilians triaged (gray) with a starting civilian population of [500]. A) and B) for the Q6_7 (Dirty bomb) scenario with ratios of first responders to civilians of 1:2 and 1:10 respectively and C) and D) for Q7_7 (plume from radioactive waste fire) scenario with ratios of first responders to civilians of 1:2 and 1:10 respectively represent the percentage of first responder agents willing to triage patients with radioactive contamination in the model using external data set survey values for *"I would feel safe working/performing my normal duties during this event"* for the myradiationtolerance variable. Communication distance represents the distance (patches) over which agents can communicate their respective myradiationtolerance variable information.

4.2.2 Model 2B: Triage with Presence of Subject Matter Experts

4.2.2.1 Model 2B: Verification

For verification of Model 2B: Triage with SME, a range of values was explored for each key variable in the model including the size of the starting population of first responders, the size of the starting population of civilians, the size of the starting population of radiation SME and the range of communication distance (patches) with which the agents can exchange information. In the verification phase first responder agents were assigned a myradiationtolerance value using a normal distribution in the same numerical range as the external dataset survey values. For all Model 2B series a starting civilian population of [500] was used. In Figures 23-25 different ratios of (first responders + SME) to civilian population were used including 1:2, 1:5 and 1:10 in Figure 23, Figure 24 and Figure 25 respectively. Within each figure series separate ratios of 1:5 and 1:10 for first responder to SME were also examined. As shown in Figures 23-25, the model is performing as expected under a wide range of values.

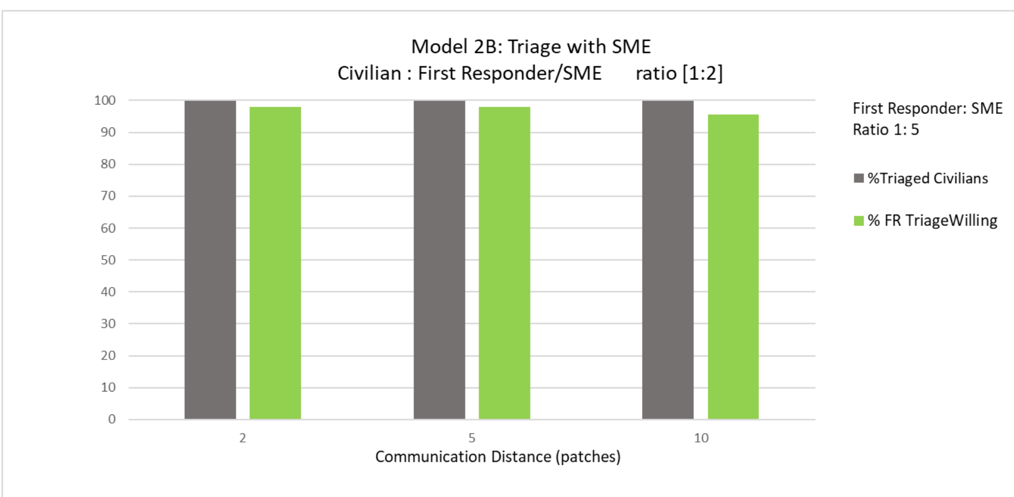
In Figure 23, where the (first responder + SME) ratio to civilians was 1:2, increasing communication had little effect on percentage of triage willing first responders when the first responder to SME ratio was 1:5 but there was a negative correlation on percentage of triage willing first responders with increasing communication when the first responder to SME ratio was decreased to 1:10. When there are less SME present, and communication increases, we see the same trend as in Model 2A: First Responders with Pocket Dosimetry, with a corresponding decrease in triage willingness.

In Figure 24, a (first responder + SME) to civilian ratio of 1:5 was used. In this series, increasing communication distance increased the percentage of triage willing first responders for both first responder to SME ratios of 1:5 A) and 1:10 B) at communication distance of [5] patches but decreased again at [10] patches. For this ratio series, it appears that as communication increases to [5] the probability of communicating with a SME correspondingly increased the triage-willing percentage but at communication distance of [10] the probability of including more regular first responders lowered the mean myradiationtolerance and decreased the number of triage-willing first responders.

In Figure 25, a ratio of (first responder +SME) to civilian of 1:10 was used. In this series with a much lower number of first responders present, a positive correlation between increasing percentage of triage-willing first responders with increasing communication was seen. This held true for both the first responder to SME ratios of 1:5 A) and 1:10 B). In Figure 25 A) a higher ratio of first responder to SME of 1:5 resulted in higher percentage of triage-willing first responders at all communication values compared to Figure 25 B) with a first responder to SME ratio of 1:10. This shows that when there is a smaller population of first responders in the field the positive effect of SME on first responders' willingness to triage patients with radioactive contamination is greater.

For trends in percentage of civilians triaged, we see that as the ratio of (first responder + SME) to civilians decreased from 1:2 to 1:5 to 1:10, a corresponding decrease in overall percentage of triaged civilians was seen across Figures 23-25, and when the (first responder + SME) to civilian ratio was lowest at 1:10 in Figure 25, we see a direct correlation between percentage of civilians triaged and percentage of triage willing first responders.

A)



B)

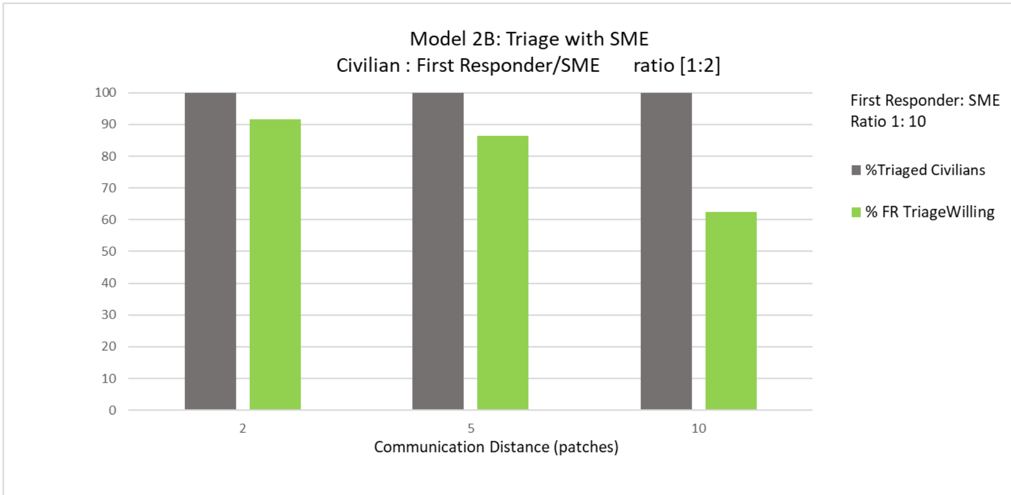
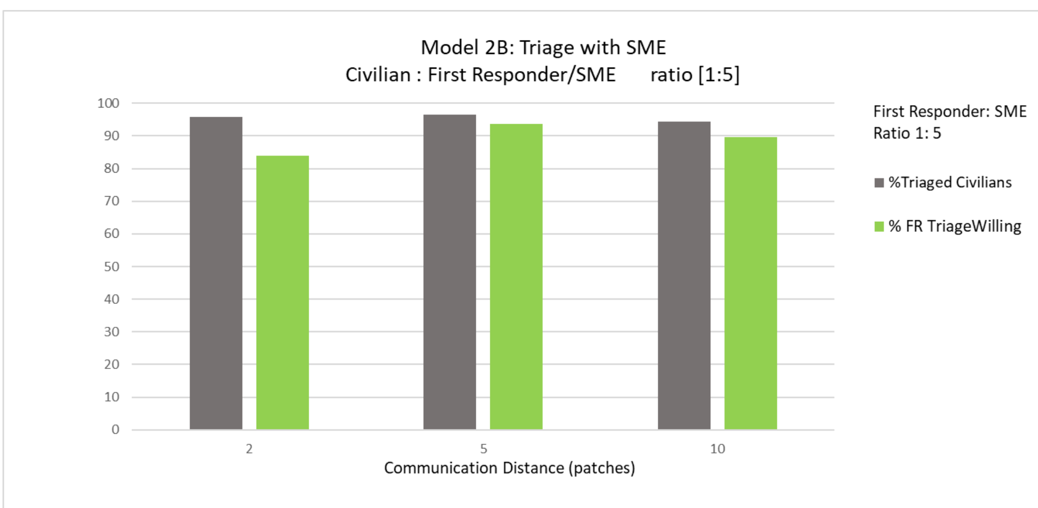


Figure 23. Model 2B: Triage with SME Model Verification

Data represents mean value from (n=10) runs of the percentage of first responder agents willing to triage patients with radioactive contamination (green) and the percentage of civilians triaged (gray). A civilian agent population size of [500] was used with a ratio of (first responder + SME) agents to civilian agents of 1:2. A secondary ratio of first responder to SME of either A) 1:5 or B) 1:10 was also included. Communication distance represents the distance (patches) over which agents can communicate their respective myradiationtolerance variable information.

A)



B)

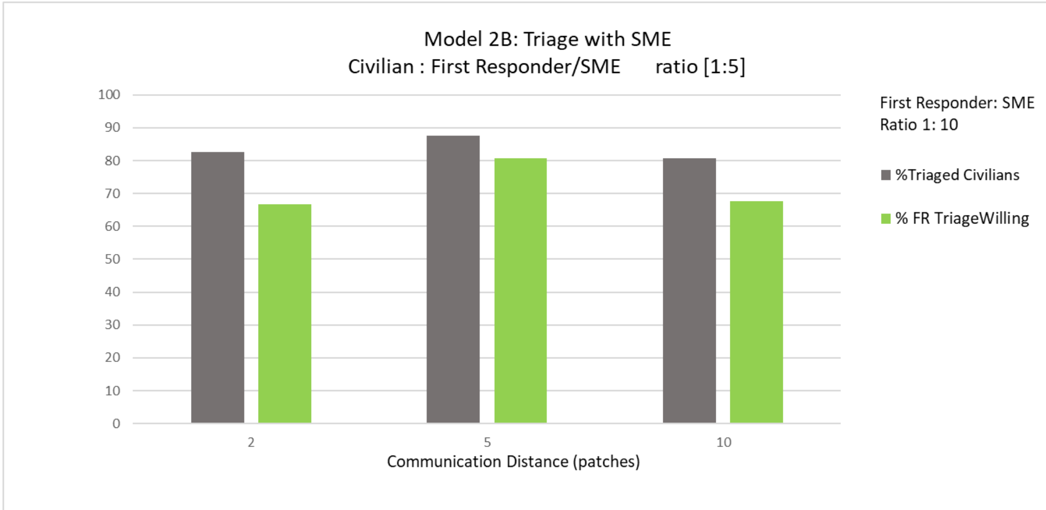
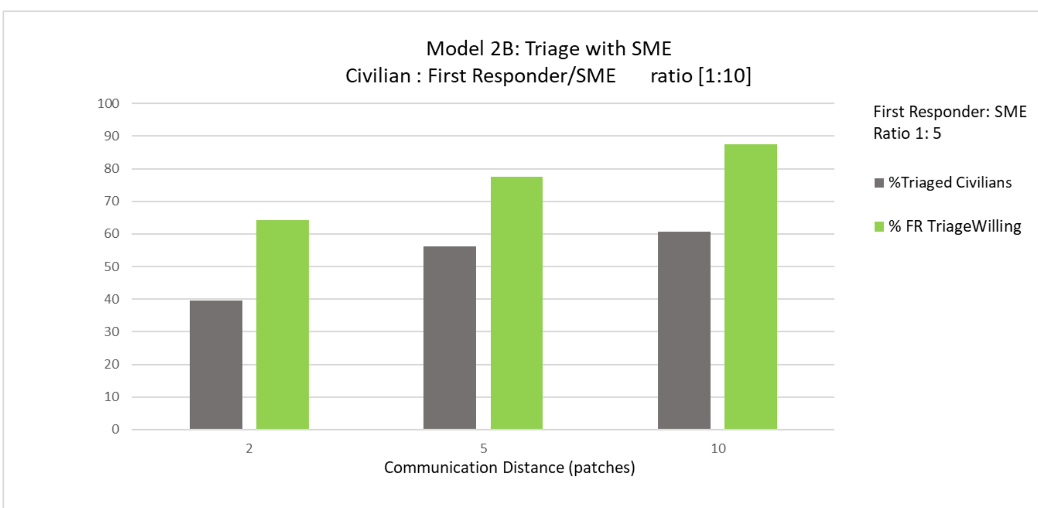


Figure 24. Model 2B: Triage with SME <u>Model Verification</u>

Data represents mean value from (n=10) runs of the percentage of first responder agents willing to triage patients with radioactive contamination (green) and the percentage of civilians triaged (gray). A civilian agent population size of [500] was used with a ratio of (first responder + SME) agents to civilian agents of **1:5**. A secondary ratio of first responder to SME of either A) 1:5 or B) 1:10 was also included. Communication distance represents the distance (patches) over which agents can communicate their respective myradiationtolerance variable information.

A)



B)

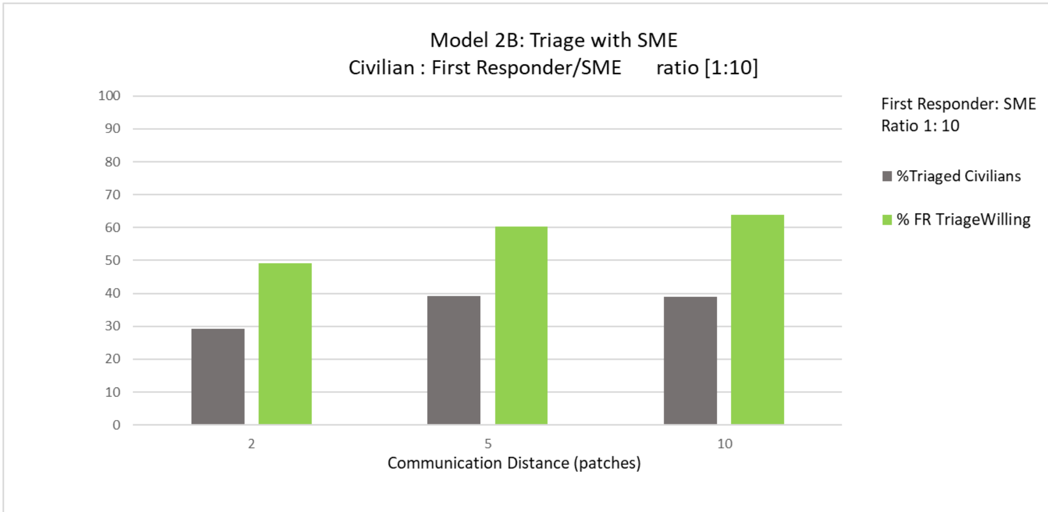


Figure 25. Model 2B: Triage with SME Model Verification

Data represents mean value from (n=10) runs of the percentage of first responder agents willing to triage patients with radioactive contamination (green) and the percentage of civilians triaged (gray). A civilian agent population size of [500] was used with a ratio of (first responder + SME) agents to civilian agents of 1:10. A secondary ratio of first responder to SME of either A) 1:5 or B) 1:10 was also included. Communication distance represents the distance (patches) over which agents can communicate their respective myradiationtolerance variable information.

4.2.2.2 Model 2B: Calibration

For calibration of Model 2B, the same external data set sourced from the Turner et. al study, which includes survey responses to a series of statements regarding first responders' willingness to work during two scenarios where radioactive contamination is present was used (3). From this survey dataset, participant scores for the statement *"I would go to work if my employer requested it, even if it was not required"* translated as "willingness to work" (WTW) were substituted in the model for values for the myradiationtolerance variable and model variables for communication were calibrated so that the percentage of first responders willing to triage patients with radioactive contamination entering the radioactive contamination matched the reported WTW percentages reported in the survey. This was completed for both the Q6 and Q7 scenarios with a starting first responder population in the model of [433] to match the number [433] of survey respondents, a 1:10 ratio of SME to first responders and a starting civilian population of [500].

For this model series, the external data set values are directly applied to the agents so that the external data set WTW values should be translated explicitly in the model into “willingness to triage” values within the algorithm. As this model directly applies WTW values to the initial baseline myradiationtolerance distribution, the model was calibrated to communication [0]. As shown in Table 7, Model 2B for the Q6 scenario, the survey data reported a 68.4% WTW and the model was calibrated to 67.9% willingness to triage. For Model 2B for the Q7 scenario, the survey data reported a 73% WTW and the model was calibrated to 71.6% willingness to triage. Percentage of civilians triaged for the Q6 and Q7 scenarios was 99.9%. Since communication was calibrated to [0] the presence of SME had no effect. Also, with a civilian population of [500] and a first responder agent population of [433] to match the external data set values, this near 1:1 ratio of first responder to civilian is reflected in the near 100% triaged civilian values. (Table 7)

Table 7. Model 2B: Triage with SME <u>Model Calibration</u>

*the number of agents populated in the model 433, directly correlates with the number of survey respondents

€ this represents a 1:10 ratio of SME to first responder

**patch distance over which the agents can communicate and share their respective mineradiationtolerance values

^ a starting population of [500] civilian agents was held constant from the verification series

~ final model calibration WTW [triage-willing=true] percentage represent mean of 10 runs

Model Calibration with External Data Set: First Responder Survey Data	
Model Calibration to Survey Question:	**WTW**
Q6_1 WTW in Dirty Bomb Scenario	**68.4%**
Model 2B Triage with SME	
Model 2B Q6_1 Calibration Variables	
First Responders starting population [433]*	
SME starting population [43]€	
Civilian starting population [500]^	
Communication Distance [0]**	
First Responoders with [triage-willing = true]	**67.9%~**
Civilians with [triaged = true]	**99.9%**
Model Calibration to Survey Question:	**WTW**
Q7_1 WTW in Radioactive Plume from Radioactive Waste Fire	**73%**
Model 2B Triage with SME	
Model 2B Q7_1 Calibration Variables	
First Responders starting population [433]*	
SME starting population [43]€	
Civilian starting population [500]^	
Communication Distance [0]**	
First Responoders with [triage-willing = true]	**71.6%~**
Civilians with [triaged = true]	**99.9%**

4.2.2.3 Model 2B Novel Findings

Following verification and calibration, survey data values for the statement "*I would feel safe working/performing my normal duties during this event*" were substituted for the myradiationtolerance variable in Model 2B using the calibrated values based on the WTW: "*I would go to work if my employer requested it, even if it was not required"* survey statement response values. With this substitution, the percentage of first responders willing to triage patients with radioactive contamination (triage willing) decreased from 67.9% to 36.9% with the Q6 dirty bomb scenario and from 71.6% to 44.9% for the Q7 Radioactive plume scenario as shown in Figure 26. This is essentially a direct application of the external data set values to the agents' myradiationtolerance. This may be interpreted to mean that if estimates of first responders' personal comfort level in providing medical treatment and triage to patients with radioactive contamination is the only factor considered, that WTW may be dramatically lower. Percentage of triaged civilians remains unaffected by percentage of triage willing first responders as the model is flooded with a large first responder population at a first responder to civilian ratio of approximately 1:1.

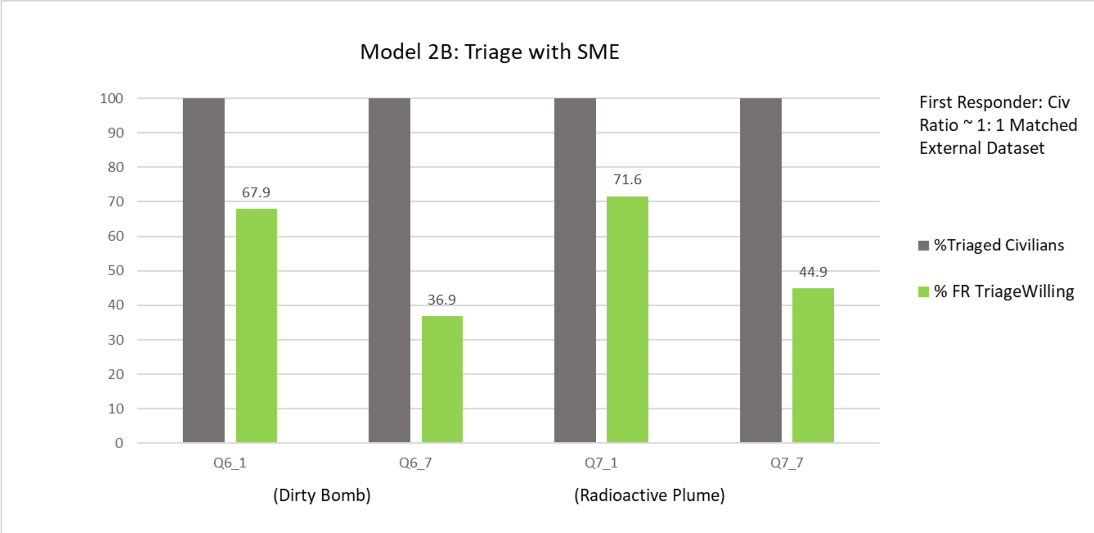


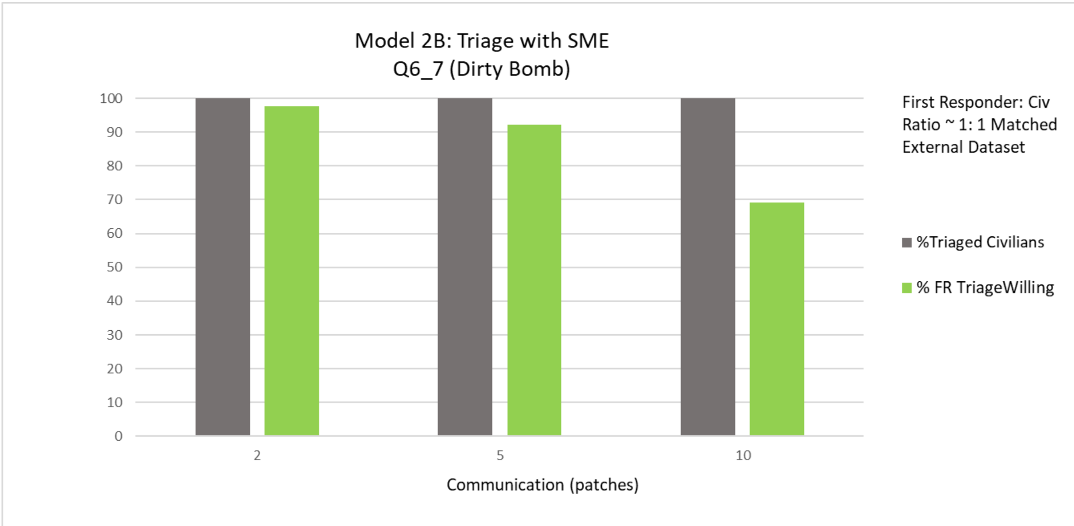
Figure 26. Model 2B: Triage with SME <u>Novel Findings</u>

Data represents mean value from (n=10) runs of the percentage of first responder agents willing to triage patients with radioactive contamination (green) and the percentage of civilians triaged (gray). Q6_1 and Q7_1 represents the percentage of first responder agents willing to triage patients with potential radioactive contamination in the calibrated model using external dataset survey values for *"I would go to work if my employer requested it, even if it was not required"* survey statement for Q6 (dirty bomb) or Q7 (plume from radioactive waste fire) scenarios for the myradiationtolerance variable. Q6_7 and Q7_7 represent the percentage of first responder agents willing to triage patients with potential radioactive contamination in the calibrated model using external data set survey values for *"I would feel safe working/performing my normal duties during this event"* for the myradiationtolerance variable. This includes a starting first responder population [433] and civilian population of [500].

Following this direct comparison of the survey data for *"I would feel safe working/performing my normal duties during this event"* and its effect on output in Model 2B using the calibrated settings, we sought to examine the effect of changes to the communication variable. Figure 27 A) (Q6 dirty bomb) and B) (Q7 plume from radioactive waste fire) shows the effect of communication distance on percentage of first responders willing to triage patients with radioactive contamination.

If all other variables are held constant and only communication is changed, as communication distance widens more agents can communicate their myradiationtolerance and depending on the preexisting myradiationtolerance population distribution, may negatively affect willingness to triage (as the mean mineradiationtolerance may be driven lower with a larger "n"). In this dataset, increasing communication reduces the percentage of first responder agents willing to triage patients with radioactive contamination as shown for both the Q6_7 (dirty bomb) and Q7_7 (plume from radioactive waste fire) scenarios in Figure 27 A) and B) respectively. Though SME are present in this data series at a ratio of 1:10, the first responder population is so large [433] that their presence does not significantly mitigate the effect of the larger "n" size on the mean myradiationtolerance value. It is, however, significant to note that the overall triage willing percentages in this model (Model 2B) as shown in Figure 27 A)- B) are significantly higher than in the same data series with matched conditions in Model 2A without the presence of SME as depicted in Figure 21 A)-B). The percentage of triage willing first responders did not significantly affect the percentage of triaged civilians in this data series as the ratio of first responder to civilian was near 1:1.

A)



B)

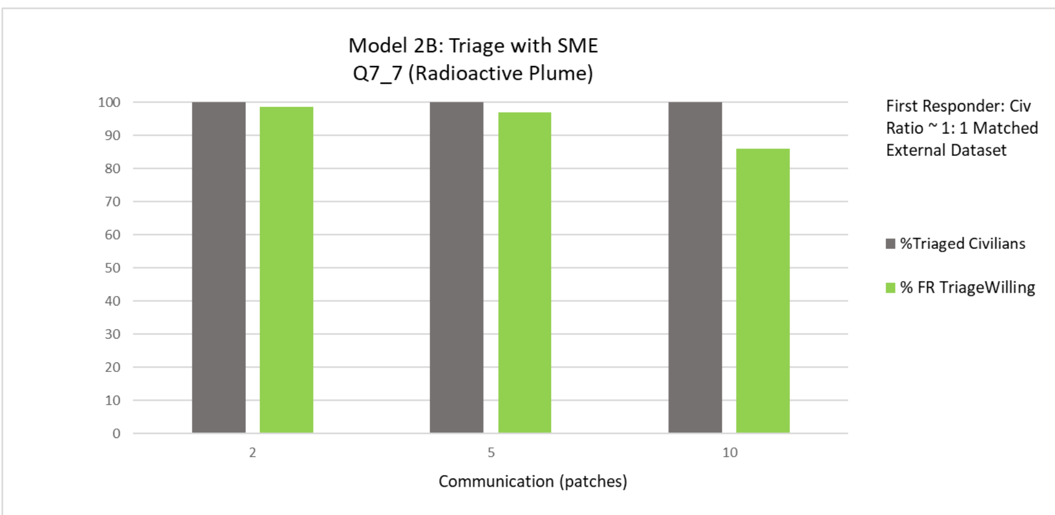
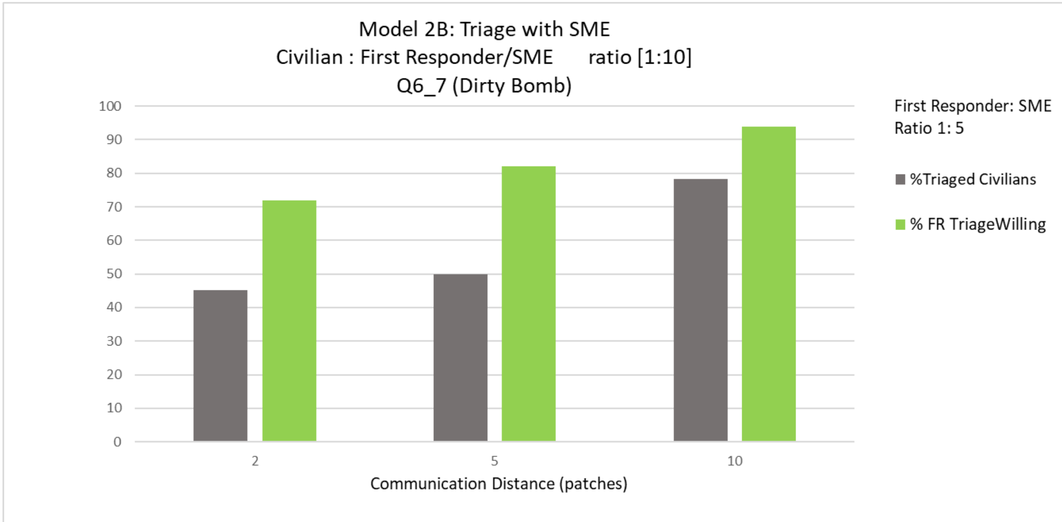


Figure 27. Model 2B: Triage with SME <u>Novel Findings</u>

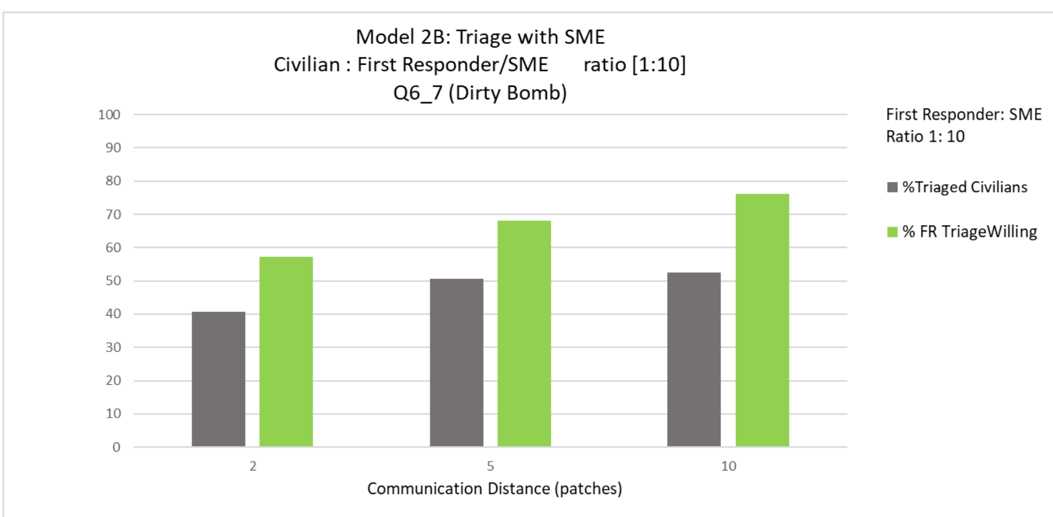
Data represents mean value from (n=10) runs of the percentage of first responder agents willing to triage patients with radioactive contamination (green) and the percentage of civilians triaged (gray). A) Q6_7 (dirty bomb) and B) Q7_7 (plume from radioactive waste fire) represents the percentage of first responder agents willing to triage patients with radioactive contamination in the model using external data set survey values for *"I would feel safe working/performing my normal duties during this event"* for the myradiationtolerance variable. Communication distance represents the distance (patches) over which agents can communicate their respective myradiationtolerance variable information. This includes a starting first responder population [433] and civilian population of [500].

We also examined outcomes in the calibrated model with more realistic ratios of first responder to civilians in a mass casualty medical management situation. For Model 2B: Triage with SME, a ratio of (first responders + SME) to civilians of 1:10 was used in addition to sub-ratios of first responder to SME of 1:5 and 1:10. These values were selected to simulate more realistic medical management scenarios. For both the Q6_7 (dirty bomb) and Q7_7 (plume from radioactive waste fire) scenarios with the (first responder + SME) ratio of 1:10, there was a positive correlation between increasing communication distance and increasing percentage of triage willing first responders (Figure 28 A-D). In both scenarios, there were also higher overall values of triage willing first responders when more SME were present as evidenced in Figure 28 A) vs. B) and C) vs. D) where first responder to SME ratios of 1:5 vs 1:10 were modeled. Within this data series, the percentage of triaged civilians also positively correlated with percentage of triage willing first responders.

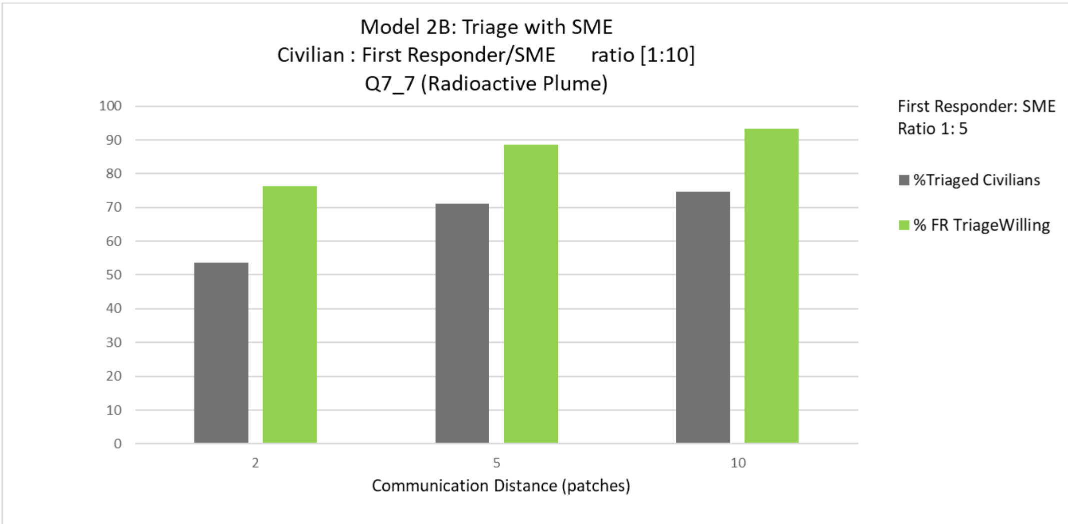
A)


Model 2B: Triage with SME
Civilian : First Responder/SME ratio [1:10]
Q6_7 (Dirty Bomb)
First Responder: SME
Ratio 1: 5
%Triaged Civilians
% FR TriageWilling
100
90
80
70
60
50
40
30
20
10
0
2
5
10
Communication Distance (patches)

B)


Model 2B: Triage with SME
Civilian : First Responder/SME ratio [1:10]
Q6_7 (Dirty Bomb)
First Responder: SME
Ratio 1: 10
%Triaged Civilians
% FR TriageWilling
100
90
80
70
60
50
40
30
20
10
0
2
5
10
Communication Distance (patches)

C)



D)

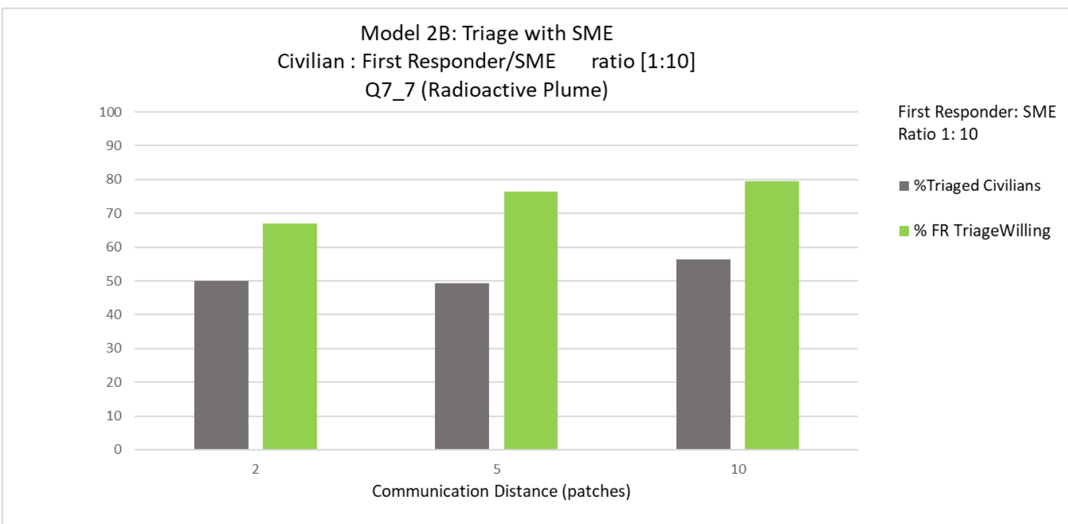


Figure 28. Model 2B: Triage with SME <u>Novel Findings</u>

Data represents mean value from (n=10) runs of the percentage of first responder agents willing to triage patients with radioactive contamination (green) and the percentage of civilians triaged (gray) with a starting civilian population of [500]. A) and B) for the Q6_7 (dirty bomb) scenario includes a ratio of (first responders + SME) to civilians of 1:10 and a ratio of first responder to SME of 1:5 and 1:10 respectively. C) and D) for Q7_7 (plume from radioactive waste fire) scenario also includes a ratio of (first responders +

SME) to civilians of 1:10 and a ratio of first responder to SME of 1:5 and 1:10 respectively. These data represent the percentage of first responder agents willing to triage patients with radioactive contamination in the model using external data set survey values for *"I would feel safe working/performing my normal duties during this event"* for the myradiationtolerance variable. Communication distance represents the distance (patches) over which agents can communicate their respective myradiationtolerance variable information.

4.3 Results Summary

These data collectively represent the output from four distinct agent-based NetLogo models designed to model the phenomena of radiation dread in first responders responding to an emergency where radiological contamination may be present. The results for Models 1A and 1B are delivered in terms of percentage of first responders willing to enter an area with radioactive contamination, and Models 2A and 2B in terms of percentage of first responders willing to triage patients who may be contaminated with radioactive materials with a secondary variable for percentage of triaged civilians. Both model series 1 and 2 utilize unique approaches to examine factors affecting radiation dread of first responders including communication, presence of radiation SME and relative respective agent population ratios. These data illustrate factors which may affect agent-based decisions to accept personal risk from radiation exposure in the context of both individual choice and the influence of group dynamics dependent on the inherent population distribution of perceived risk as defined by the myradiationtolerance variable in this series. Together these data examine complex social dynamics of individuals in groups, the influence of social interaction on behavior, and perception of risk from radiation exposure.

CHAPTER 5 – DISCUSSION

5.1 Model Overview

Computational modeling is a useful research approach for exploring variables and dynamics which affect complex systems. When modeling socially complex systems, agent-based modeling is a valuable approach as it enables each agent to make independent decisions based on input from the designed environment and interactions with other agents. For this model series, I wished to explore factors related to radiation dread and first responders' willingness to enter areas with radioactive contamination or provide medical treatment to patients who may be contaminated with radioactive contamination.

5.1.1 Model 1 Series: First Responders Willingness to Enter an Area with Radioactive Contamination

For the Model 1 Series: First Responders Willingness to Enter an Area with Radioactive Contamination, the model was based on movement and interactive association of the first responder agents with each other and with the addition of radiation subject matter experts (SME). The model assumed that the first responders had either pocket dosimetry, or some instrumentation with the ability to determine if ionizing radiation was present. SME were assumed to have additional expertise in risk assessment specific to exposure to radiation and accumulated radiation dose. Agents in the model were randomly assigned a "myradiationtolerance" value from within the external data cohort series and their position was also randomly generated. This model was based on interactions with physical movement and communication of information, namely each agents' respective myradiationtolerance score.

Though in a real-world scenario it is expected that first responders from certain teams would have established associations, in a mass casualty management scenario, it is also reasonable to assume that first responder groups would interact with other individuals, or groups of individuals, which they previously have had no association. Therefore, agent association and movement in the model was designed to be organic in nature with the agents allowed to self-organize and first responder agents were not assigned to specific teams. This allowed agents to form groups with their neighbors and their mean myradiationtolerance score to influence their willingness to enter an area with radioactive contamination.

In this model we observed several notable trends in agent behavior. Firstly, it was not surprising that the issue of willingness to work (WTW), as translated in the current model as willingness to enter an area with radioactive contamination, was shown to be a prominent issue within the modeled setting. As shown in Figure 8 (without SME) and Figure 13 (with SME), the percentage of WTW output in the model when using the Q6_1/Q7_1 data set of reported survey responses for "*I would go to work if my employer requested it, even if it was not required*" was dramatically higher than when using the Q6_7/Q7_7 data of reported survey data for "*I would feel safe working/performing my normal duties during this event*." This trend was similar in both Model 1A (without SME) and in Model 1B (with SME). This was not surprising however as this series of runs used the constrained settings from the calibration phase which used a small number of SME [10] within a [433] first responder population size and limited communication to the lowest setting [2] as well. The addition of SME did however have a slightly higher WTW than the model without SME as in Figure 8 (without SME) the WTW for Q6_7 and Q7_7 was 3.7% and 5.5% respectively and in Figure 13 (with SME) it was 4.9% and 7.4 respectively. This dramatically illustrates the potential real-world phenomena of radiation dread within the context of the current modeling scenario.

Secondly, one surprising feature was found to be that the influence of the communication variable did not always have a positive correlation with perception of radiation risk. With increasing ability to communicate, there was not a commensurate increase in WTW. Instead, the importance of the underlying distribution of myradiationtolerance values within the agent population, size of that population and ratio of first responder to SME were found to be the driving factors.

If the myradiationtolerance distribution values were generally low then with increasing communication, WTW decreased. This was very notably seen in Figure 9 (without SME) and Figure 14 (with SME). For these model runs, as the ability to communicate increased, i.e., each agent could talk with a greater number of surrounding agents as the patch distance increased from [2] to [10], the WTW correspondingly decreased. It may seem counterintuitive that the model runs with SME also demonstrated a downward trend in WTW, but this is due to the specific constraints of this model run series. For this run series the model was still using a [433] first responder/ [10] SME population so the ratio of first responder to SME was too low to have a significant effect, though the WTW values with SME were slightly higher than without SME. At communication [2], (4.9% WTW for Q6_7 and 7.4% for Q7_7 in Figure 14 (with SME) vs. (3.7% WTW for Q6_7 and 5.5% WTW for Q7_7 in Figure 9 (without SME).

The observed phenomena of the influence of communication on WTW was also magnified by the size of the population. For example, the effect on WTW from increase communication was not consistent across population size. As shown in Figure 11, with starting population sizes between [20] and [400] and first responders communicating over patch distances of [2], [5] and [10], when communication was held constant at [2] increasing population size corresponded with increasing WTW, but when communication was set at [5] WTW initially increased and then consistently decreased at the population size increased. This is explained by the effect of the preexisting distribution of the myradiationtolerance within the population. When the agents are limited to communication [2] as the population increases there is a greater likelihood that they will interact with another agent with a higher myradiationtolerance than themselves up to a certain threshold. When the agents have a communication distance of [5] or [10] the likelihood that they will interact with more agents that have lower myradiationtolerance values (dependent on the preexisting distribution of myradiationtolerance values of the population) results in less overall WTW. Addition of SME was shown to have an overall positive influence as in Figure 11 (without SME) the overall WTW never rose above 20% and in Figure 17 (with SME) it was shown that if you add enough SME you can achieve WTW values approaching 100%.

In a real world setting this translates simply to first responders talking with each other. If they are in a small group, the influence of radiation dread might be less than in a large group, where if the majority of the individuals have high levels of radiation dread they drown out or even negatively influence the individuals with less radiation dread.

The ratio of first responder to SME was also dependent on communication, as the mean myradiationtolerance value at certain communication distances and population sizes was affected by a first responder agent being statistically more likely to communicate with additional first responders which may lower the group mean, or communicate with a SME which would increase the group mean. Since the group myradiationtolerance mean directly influences overall WTW output measured in the model, this is important. As Figure 17 demonstrates, in both scenarios for Q6_7 and Q7_7, as you increase the number of SME from [10] to [50] there is an overall increasing trend of WTW. The effect of communication is also seen in this run series, which includes the presence of SME. Figure 17 illustrates that irrespective of the overall starting number of SME in a population, when communication distance is held constant, as the population increases the WTW decreases. This is because as the population increases, the ratio of SME to first responder is diluted and it is statistically less likely for the first responder agents to interact with a SME. At all iterations however, the inclusion of SME agents increased the overall WTW at the same corresponding population sizes as compared to those without SME as shown in Figure 11.

These figures highlight the major findings of the model which are that presence of SME increase WTW and that communication can be used as a tool to increase WTW when SME are present in influential numbers, but that increasing communication without SME may cause the converse and decrease WTW. In a real-world scenario this translates to having a “boots on the ground” SME present during emergency response. In this model series, the SME may be interpreted to represent a first responder with specific training for radiological hazards, or a radiation health science professional, such as a certified health physicist (CHP) or radiation safety officer (RSO).

In the Model 1 series, the coded algorithm allowed for both positive and negative effects of the mean myradiationtolerance value from neighboring agents. This was intended to translate to a scenario where a first responder's colleagues' perception of risk from radiation exposure may affect their own in either a positive or negative direction. In a real-world setting, a first responder who holds a high level of concern about radiation exposure may talk to his colleagues who are less concerned about radiation risk and then decide to accept this risk. Or a first responder who is not worried about radiation exposure may be influenced by his more concerned colleagues and decide not to accept the risk as well. This behavioral algorithm was applied to the willingness to enter an area with radioactive contamination model simulating first responders preparing to conduct emergency operations and enter a potentially contaminated area. With the addition of SME in this scenario, it is reasonable to assume that having a subject matter expert or colleague with hazard specific training alongside will increase confidence and lower perception of risk in first responders who are unfamiliar with the comparative health risks of radiation exposure.

5.1.2 Model 2 Series: First Responders Willingness to Triage Patients with Radioactive Contamination

For the Model 2 Series: First Responders Willingness to Triage Patients with Radioactive Contamination, the model was based on a decision tree where first responder agents followed a guided decision-making process to determine whether they would engage in triage of potentially contaminated patients. Factors affecting this decision process included interactive association of the first responder agents with each other and with the addition of radiation SME. This interaction was in turn, affected by physical movement to a limited degree and level of communication. The model assumes that the first responders had either pocket dosimetry, or some instrumentation with the ability to determine if radioactive contamination was present, but in the case of triage may not have time to use it, in the course of administering lifesaving medical treatment. SME were assumed to have additional expertise in risk assessment specific to exposure to radiation and accumulated radiation dose.

Agents in the model were randomly assigned a “myradiationtolerance” value from within the external data cohort and their position was also randomly generated. Their movement within the model was constrained for each agent within a specific radius but random within that radius. This was designed to simulate potential real-world movement in a triage setting where first responders would have freedom of movement and interaction with other first responders within a certain area but not across the entire setting. WTW in this model is defined as willingness to engage in triage of patients potentially contaminated with radioactive material. WTW was determined by either individual myradiationtolerance score or the mean of that value from surrounding neighbors. The model was designed so first responder agents will engage in triage if they have a high enough myradiationtolerance value assigned to them, or if the mean of their surrounding agents myradiationtolerance bumps them high enough. This was designed to simulate a scenario in the field where first responders with lower levels of radiation dread, when presented with an injured patient, might overcome their concern about personal risk from radiation exposure to treat the patient, and first responders with higher levels of radiation dread may also decide to treat the contaminated patients if surrounded by their peers actively doing so. This model assumes a medical reception center in the field or hospital emergency room setting, where an influx of injured or worried well patients would arrive requesting medical treatment. Though in a real world setting first responders in a hospital setting would have established previous associations, in a field setting, it is also reasonable to assume that first responder groups would interact with other individuals or groups of individuals, which they previously have had no association.

In the Model 2 series, similar trends in agent behavior were observed to what was seen in the Model 1 series. Namely that the addition of SME increases overall WTW and the influence of the communication variable did not always have a positive correlation with perception of radiation risk. The positive effect of addition of SME is illustrated when comparing data between runs which used the same first responder to civilian population ratios (1:10) as in Figure 22 (without SME) B) and D) as compared to Figure 28 (with SME) A) through D) data. Overall WTW percentages were consistently higher when SME were added as compared to without.

Similar to the Model 1 series, with increasing ability to communicate, there was not necessarily a commensurate increase in WTW. This is clearly shown in Figure 21 (without SME) where, as communication increases the percentage of WTW consistently decreases. However, Figure 28 (with SME) demonstrates that when SME are present in significant numbers (first responder to SME ratio of 1:5 and 1:10), increased communication consistently corresponded with increased WTW. Though not directly related to the essential question of WTW, the secondary output of percentage of triaged civilians in the model also correlated with increasing percentage of WTW as shown in Figure 28.

The effect of ability to communicate on willingness to triage was largely dependent on the underlying preexisting myradiationtolerance distribution within the agent population as applied from the external dataset "I would feel safe working/performing my normal duties during this event." In this model series, the coded algorithm allowed for only neutral or positive effects of the mean myradiationtolerance value from neighboring agents. This was intended to translate to a scenario where a first responder shows up for work and is presented with an injured patient who may or may not be contaminated with radioactive material and must decide whether perception of risk from radiation exposure outweighs the decision to triage.

In this scenario, seeing a colleague engage in triage and accept some form of personal risk to render medical treatment may positively influence the first responder who was worried about radiation exposure, but others refusing to render aid would not influence the first responder who had already decided they were willing to treat injured patients. Major findings in this model series primarily include that the addition of SME within the scenario consistently increased the overall WTW and that increasing communication is most effective at mitigating radiation dread when SME are present in significant numbers.

5.2 Key Findings

The major findings from these model series consistently illustrate that 1) radiation dread and WTW is a significant issue which needs to be addressed for mass casualty medical management of events involving radiation, 2) that the presence of SME are a powerful moderator of radiation dread and may increase WTW and finally 3) that communication is a two-edged sword and its use as a tool in mitigation of radiation dread should be carefully utilized during an actual radiological or nuclear event in consideration of the pre-existing levels of radiation dread within a given first responder population and number of SME present. The current study utilizes two different modeling scenarios using different algorithms for modeled behavior. Though the Model 1 Series simulates willingness to enter an area with radioactive contamination and the Model 2 Series simulates willingness to medically treat patients contaminated with radioactive materials, the applications of the findings are highly similar. Whether a first responder must contemplate receiving a radiation exposure during search and rescue or administer life-saving medical treatment for contaminated patients, the issues of radiation dread, the effect of social influence from peers to influence an individual's perception of risk, and the mitigating influence of SME when facing unfamiliar hazards remains essentially the same.

This is further supported in the study through use of survey data from two different scenarios, one including a naturally occurring radiation hazard (Q7_7) and the other a terrorist incident where radioactive materials are present (Q6_7). The major findings from the study remained consistent across these different types of radiation incident scenarios indicating that the principles of WTW, mitigation of radiation dread through SME and variable effect of communication based on the pre-existing distribution of relative radiation tolerance in a population, are applicable for a wide range of emergency response scenarios involving radiation hazards. These study findings illustrate the critical need to develop policies which address WTW phenomena, validate the essential value of SME in mitigating perception of risk and provides a useful framework for development of future polices to do so.

5.3 Model Validation

In these models an external data set of survey responses regarding first responders' willingness to work and personal feeling of safety as interpreted by their survey responses to the statements: "I would go to work if my employer requested it, even if it was not required" and "I would feel safe working/performing my normal duties during this event" were used to calibrate and generate novel findings in the models (3, 157). Though the models were calibrated with the "willingness to work" survey response distribution translating into output values for willingness to enter an area or treat patients with radioactive contamination, this application is a best fit scenario and does not explicitly correlate. The assumption that the "I would feel safe" survey values also translate to willingness to enter an area or treat patients with radioactive contamination also does not explicitly correlate.

Yet the assumption to use "I would feel safe" survey values was made on the basis that the reported willingness to work scores may not translate literally were an actual event to occur and that the "I would feel safe" survey values are more reflective of the perception of risk and phenomena of radiation dread. It cannot be assumed however, that the values for "I would feel safe" are as low in willingness to enter an area with radioactive contamination or treat contaminated patients, as they are in the model output in absolute terms. A first responder answering that survey question could personally not feel safe at all, and still decide to show up for work and accept the added risk of radiation exposure. However, the growing body of literature which illustrates the issue of radiation dread affecting reported willingness to work of first responders during radiological or nuclear events supports the use of this dataset as a best fit application within this model series to explore social factors which affect perception of risk and radiation dread (197).

The external dataset also utilized two different scenarios, where first responders were asked to respond to either a scene where a dirty bomb has been detonated or where there was a plume from a radioactive waste fire. Survey data from both scenarios were applied to the models in this study, as the expectations of the first responders' duties in each of these events are directly relevant to both model series in this study. In the survey scenarios, first responders would either be entering incident scenes were physical contamination will be present or providing medical aid to victims who may be contaminated with radioactive material.

Support for the main behavioral algorithm in both model series, which allows agents to make decisions regarding personal risk based on communication of perceived risk from their colleagues is found in one survey study of first responders, which reported that respondents were more likely to report that they were willing to work during a radiological or nuclear event if they perceived that their colleagues would as well (4). Findings from other studies which indicate that perception of personal risk to radiation exposure is mitigated more strongly through provision of physical personal protective equipment over dosimetry information or risk guidance from established trustworthy sources, further support the model assumption that mitigation of radiation dread by lowering perception of personal risk through inclusion of the physical presence of SME is sound (129, 158). Placing greater trust in information provided from established familiar sources when considering unfamiliar threats, such as from a dirty bomb, has also been shown (136). In a practical sense, this is interpreted in the model as having SMEs in the field alongside the first responders facing the risk vs. first responders being provided offsite expert guidance on the hazard.

Overall, the assumption that peer influence affects behavior is based on accepted theorems of the psychology of social interactions and social influence network theory. A pivotal theory by Latane, proposes that the effect of combined social interactions are a multiplicative function based on the "strength," "immediacy" and the number of influencers in a given social group. In other words, social impact can be represented as the average of neighbors' opinions (198). Social influence network theory in turn, uses mathematical modalities to characterize the social process of changing attitudes of individuals within a social network (199, 200). This body of literature supports the assumption in the model that the average value of the myradiationtolerance variable within a set communication range will influence the behavior of individual agents in an interactive setting. Though no external data set is currently available which explicitly matches the needs of this model series, reasonable assumptions for modeled behavior based on current findings in the literature and application of the best matched available data set were used to validate the current findings.

5.4 Model Limitations

Computational modeling is intrinsically bounded by the limitations of its construction. A model cannot include every variable when simulating real world phenomena. When modeling social phenomena, the key variables must be limited to only those most relevant to the social behavior the model is designed to study and in consideration of the constraints of available processing power and the accessibility of external data sets.

In both model series built for this study, additional agent and environmental variables were included which, while not expressly needed to answer the main hypothesis query, helped frame the social and environmental behavior of the model. In the Model 1 Series: First Responders Willingness to Enter an Area with Radioactive Contamination, the model included areas with simulated radioactive contamination and variables for both deposited fallout radioactive material and a radiation point source. These values were arbitrarily assigned. An algorithm allowing agents to alter their movement behavior upon encountering the contaminated area was also included. In the model this translates to agents adjusting their movement to avoid higher radiation areas while still advancing within the contaminated zone. This coded behavior was not explicitly needed, as the essential output variable of interest was only whether they entered the area at all, but was designed to reasonably mimic first responder behavior in a real world scenario provided similar context.

Similarly, in the Model 2 Series: First Responders Willingness to Triage Patients with Radioactive Contamination, the model included code to simulate triage with arbitrarily assigned health scores representing injury within the civilian agents and coded behavior for the first responders interacting with civilian agents, rendering medical treatment and an algorithm for movement of civilians exiting the area. These behaviors and the civilian agent population itself were not expressly needed, as the main output variable of interest was how the first responder agents' interactions with each other and SME, affected whether they were triage-willing. They did not need to perform actual triage. Yet this extra coded behavior helps to visualize the model scenario and provide a secondary variable of number of civilian agents triaged.

In both models these additional features serve to visually validate the behavioral context of the situation the model is designed to simulate. These variables are not calibrated to external data, either due to lack of relevance to answer the essential research question, or because such data sets aren't immediately accessible. For example, external data sets do not exist to calibrate health scores for combined injury from radiation exposure plus conventional blast injury, or for length of time to triage and render medical treatment for each patient. These variables and features are however, integrated into the model and could potentially be built upon for other future studies.

CHAPTER 6 – CONCLUSION

6.1 Application of the Research

Though there is a notable body of literature examining the existence of radiation dread and issue of willingness to work for future radiological or nuclear events amongst first responders and other hospital personnel, this phenomena is not explicitly mentioned, nor strategies developed to address this concern in the national Concepts of Operations and emergency planning and preparedness guidelines for radiological and nuclear events. Our model series simulated social interactions between first responders using two different sets of assumptions regarding behavioral interactions in two diverse model environments. These models highlight factors which might affect mitigation of radiation dread and provide observational data with applications for command-and-control policy development. The models were based on agents having limited information and highlighted the dynamic effect of communication and information sharing on perception of individual personal risk.

Key findings from the current study suggest that the inherent makeup of the starting population both in terms of numerical size and preexisting, individually held levels of radiation dread, and the ratio of first responders to radiation SME are dynamic factors which affect risk perception and willingness to work. These findings also demonstrated that the role of communication and the presence of radiation subject matter experts are important elements which can be leveraged to mitigate risk perception and willingness to work in a radiological or nuclear event setting.

6.2 Policy Implications

These findings have implications for policy development in planning and preparedness for mass casualty medical management of a radiological or nuclear event. Currently, there do not exist explicit policies in national planning and preparedness guidelines which address the phenomena of radiation dread and first responder WTW during future radiological or nuclear events. Though this phenomenon has been relatively well-documented in the literature, through survey studies of first responders and hospital personnel, policy development to address this potentially critical confounder for successful emergency response for future radiological or nuclear events remains an unmet need (197).

Firstly, this modeling study through use of computational methodologies and application of established theories of social science behaviors adds to this growing body of research by illustrating the issue of radiation dread and first responders' WTW in a novel way. Though great strides have been made at the national level to prepare for future radiological or nuclear events, including comprehensive planning playbooks, protective action guidelines, radiation specific medical countermeasures and systems to diagnose and triaging radiation injury, none of these important resources can be utilized effectively without a first responder work force. Tackling first responder WTW during an event with radiation hazards is the next critical phase of emergency planning and preparedness, which needs to be addressed.

Secondly, the findings of the current study show that first responder groups with the presence of radiation SME had higher WTW than those without, emphasizing the importance of this specific expertise during emergency response to unfamiliar CBRN type events, such as a radiological or nuclear event scenarios. Thirdly, though it may be intuitive to assume that enhanced communication will mitigate perception of radiation risk, the current findings indicate that communication only mitigates radiation dread when there are more communicants with lower levels of radiation dread i.e., less people who are worried about radiation exposure. If the first responder population is predominantly made up of individuals with high levels of fear of radiation exposure, increased communication will worsen the problem and result in lower overall WTW. If, however, the first responder population is made up of individuals with a mixed distribution of levels of fear and there is a greater percentage of individuals with less fear of radiation exposure, increased communication may result in higher overall WTW.

This study illustrates that the underlying information being communicated is a key variable for mitigation of personal perception of risk and highlights the value of radiation subject matter experts in the field. This has implications for integration of radiation SME and how communication tools might be best utilized during emergency response to an event where radiation hazards are present. From a command-and-control perspective, prioritizing communications access and a continual communications presence for SME during active operations should be useful for mitigating concerns of first responders regarding radiation exposure. Policies which support utilization of local SME who have existing working relationships with first responder groups over outside federal support should also be developed.

The current planning documents for emergency response for radiological and nuclear events include a host of available federal radiation SME assets that might be deployed in the case of an incident including those from the Department of Homeland Security (DHS), the Department of Defense (DOD), the Department of Energy (DOE), the National Nuclear Security Administration (NNSA), and the Radiation Emergency Assistance Center/Training Site (REA/CTS) and many others (63). In a real-world scenario, SME communicating remotely or perhaps SME unfamiliar with local first responder groups, such as those provided by federal assets may not be as effective in mitigating radiation dread, as a local SME known to the community. As communication in this study was shown to be critical in enhancing the positive effect of SME on WTW during a radiological or nuclear event, policies which prioritize the importance of leveraging existing SME, enhancing their ability to communicate and to be in leadership roles during a future event are key. Radiation SME provided through federal response efforts might be deployed in support of local SME rather than in direct contact with local first responders to increase confidence in the guidance being provided for health safety.

At the local level of emergency response, the current study findings might be used to implement policies for mitigation of radiation dread, by illustrating the need to conduct preliminary surveys of specific first responder workforces to determine the preexisting distribution of WTW of a given group. Resources might then be allocated for integration of local SME within groups with the lowest WTW responses or for creation of SME through additional training. The findings of this ABM modeling study also illustrate the positive impact that SME can have on a group's risk perceptions and the importance of radiation SME to be familiar to the first responder group, in positions of leadership and able to communicate effectively within the group.

At the federal level of emergency response, similar surveys evaluating radiation dread and WTW in federal response personnel might be conducted. Radiation hazard specific training is not necessarily prioritized across the federal landscape and such surveys may reveal that additional training is required. In the event that low WTW of local first responders hinders effective emergency response to an event, deployment of additional federal personnel who have received radiation hazards specific training should be considered as a possible contingency option. Utilization of the Medical Reserve Corps (MRC), a national system of volunteer medical response personnel is already part of existing planning guidelines in the case of national disasters (201) .

Policies might be developed which provide funding and resources for education on radiation specific hazards and medical care of patients who may potentially be contaminated with radioactive material within this important response group. Historically, medical personnel have consistently refused to care for patients exposed to radiation or contaminated with radioactive material before decontamination protocols have been observed (197) . This is in direct contradiction to the consensus guideline that little to no harm will be incurred by staff caring for such patients, as they will receive very small radiation exposures. Particularly in the case of the triage setting, policies supporting having onsite radiation SME physically present demonstrating the lack of risk will be crucial for mitigating radiation dread in the workforce. Though the inclusion of radiation health science experts in the field may not be feasible for practical considerations including their lack of training in general hazards, providing general radiation hazard specific training to all first responders and enhanced radiological hazards training to specific members of first responder teams could create substitute ad hoc subject matter experts in the field. Similarly, in a medical reception center or emergency room setting, increased access to training on radiation specific hazards could help mitigate radiation dread. In this scenario, SME could be present to physically demonstrate and reassure concerned medical personnel about the relative risk of treating patients with radioactive contamination. In this setting, the SME would also need prior training to be able to integrate into the command structure in the context of medical procedures. Leveraging local existing medical personnel such as medical dosimetrists, radiation oncologists and radiology technicians has been considered but broad policies and resources to develop this untapped resource have not been enacted (179) .   REAC/TS are the established experts in the United States at integration of medical radiation SME into medical management of radiation incidents and currently deploy across the country to aide with medical management of individual cases of radiation exposure (202). SME from this organization should be considered the greatest potential asset for deployment during future events and might work alongside existing local SME in the medical setting to achieve greater effectiveness at mitigating radiation dread in medical response personnel when treating contaminated patients.

Development of programs which support formation of working relationships between radiation subject matter experts and first responders at the local level before an event are essential. The Radiological Operations Support Specialist (ROSS) program, which currently recruits and trains civilian radiation SME to be able to respond and integrate into the emergency response command structure, is one existing program that could be leveraged to meet this need (203). The ROSS program created by the Department of Homeland Security (DHS) and maintained by the Federal Emergency Management Agency (FEMA), is particularly suited to meet this need. The field of radiation health sciences consists of a broad range of radiation subject matter experts including certified health physicists, radiation safety officers and medical dosimetrists distributed amongst the government, private industry, academia and medicine with corresponding levels of expertise and experience, but not necessarily equipped with the skills to efficiently aid emergency management of an event with radioactive hazards. The ROSS program uses a tiered system to train radiation SME with different levels of authority complimentary to their relative experience and education. All ROSS trainees receive training on basic emergency management procedures and guidance for integrating into the command-and-control structure, both at the federal level and in support of state and local emergency response. The current ROSS program requires a minimum of 40 hours of in person training and sessions are not offered with great frequency or nationwide. This program could be expanded with greater funding and resources so that more radiation SME can become a ROSS through increased in person training opportunities, both in frequency and location and through development of online training platforms and refresher courses. Policies which incentivize large hospitals and first responder units near major metropolitan areas to have ROSS trained SME could help to mitigate issues with radiation dread amongst first responders.

Agencies which operate at the state and local level to support emergency planning and preparedness and public health like the National Association of County and City Health Officials (NACCHO), and the National Alliance for Radiation Readiness (NARR) would also be ideal organizations to engage in education initiatives and greater coordination between local first responders and radiation subject matter experts (65, 67). The NARR is a collaboration of many different public health, emergency management and healthcare organizations which support emergency management preparedness for emergencies involving radiation hazards at the state and local level.

This organization partnered with the NACHHO represent an existing framework and network of partnerships, which would be useful in facilitating development of a stronger body of radiation SME with first responder relationships. Finally, larger first responder agencies in more metropolitan areas, which have already established radiological threat training programs, might be incentivized to share their curriculum resources with smaller first responder groups in other geographic areas (204). The major findings of the current study suggest that development of programs which support formation of working relationships between radiation subject matter experts and first responders at the local level before an event are essential for mitigation of radiation dread.

Policies which increase access to training programs on radiation hazards and the relative health risks from radiation exposure will help mitigate radiation dread and create more local radiation SME within first responder units. Access to these programs can be facilitated through increased funding and support for these education initiatives. First responders have to maintain numerous annual trainings and certifications and additional training for low probability events such as a radiological or nuclear event hazards may not be popular. Incentivizing such training through greater access and funding may facilitate compliance and more acceptance for this additional training. Such prospective education initiatives benefit from the existence of a diverse selection of options for training on radiation hazards and it is not necessary to develop new curriculum. There are existing training programs for medical management and general emergency response for radiological and nuclear events supported through the RITN, REAC/TS, FEMA, the NARR, and a comprehensive list of both in person and online training opportunities available on the Radiation Emergency Medical Management (REMM) portal maintained by Department of Heath the Human Services (70).

Support of such education efforts on the relative health risks from radiation exposure in the context of emergency response and planning can also be expanded to the general public and should not be limited to only first responder communities. Given the current challenges faced during the COVID-19 pandemic with public acceptance of science-based health directives from government sources, further funding should be given to development of new nuclear civil defense projects, such as the nuclear civil defense project at the Stevens Institute of Technology, which seeks to modernize and improve nuclear risk communication with the American public (205). A modern civil defense program would help prepare both the general public and first responder communities for future radiological or nuclear events scenarios.

Biodosimetry diagnostics have also been developed and will soon enter the Strategic National Stockpile (SNS). These point of care diagnostics are useful for triage purposes during future radiological and nuclear events, by screening for those who have received a medically significant radiation exposure. Though it is unlikely that first responders would receive a high dose of radiation exposure, either through search in rescue activities (where handheld dosimetry equipment is accessible), or in the medical care of patients with radioactive contamination (where historically, no medical personnel caring for a patient with radioactive contamination receiving a significant radiation exposure has ever been documented), these biodosimetry diagnostics could also be made available to first responders to help mitigate their own personal concerns from radiation exposure.

6.3 Future Research

Though the findings of the current study are an important contribution to the field of emergency planning and preparedness research for radiological and nuclear events, the creation of the computational models themselves are equally important. The model series created in this study, one looking at first responders' willingness to enter areas with radioactive contamination and the other looking at first responders' willingness to triage patients potentially contaminated with radioactive materials are useful tools, which may be utilized in future research. As the models built for this study utilized algorithms specifically tailored to be compatible with common numerical survey scales, future survey data can be readily integrated within the existing model framework.

Future research directions include further refinement of the current model algorithms as relevant external data sets become available. These data sets might include other survey studies of first responders' responses regarding willingness to work during a radiological or nuclear event and their perceived personal risk from radiological hazards after training. The current study used a data set from first responders in the geographic region of the St. Louis, Missouri metropolitan area. It would be helpful to model additional data sets collected from first responders and emergency personnel in other regions of the country. Modeling the addition of radiation specific medical countermeasures including radiation biodosimetry diagnostics would also be useful in the triage model, as biodosimetry diagnostics would enhance triage procedures by allowing first responders to determine those individuals who have received a radiation exposure and require further medical treatment specific for radiation injury.

6.4 Contribution of the Findings

Current emergency planning and preparedness guides for mass casualty management of radiological or nuclear events do not adequately consider the effect of radiation dread on deployment of first responders or how subject matter experts in radiation exposure can be best integrated into mass casualty management following an event with radioactive contamination. Emergency response for radiological and nuclear event scenarios is uniquely challenging due to its highly complex, low familiarity, low probability, and highly dreaded nature. There is a need for further research into best practices for mitigation of radiation dread in mass casualty medical management of a radiological or nuclear event. The current research findings support the need for development and funding of training programs for medical personnel and support staff on the relative health risks from radiation exposure in the triage and treatment of patients contaminated with radioactive material and their own personal risk in entering areas with radioactive contamination. The current findings also support further development of policies to integrate radiation subject matter experts within the operational response. Additional research in this area will fill an unmet need for improved disaster management strategies for mass casualty management of events involving radiation injury and radiation exposure. There remain key unexplored avenues of study in the area of mass casualty medical management of radiological and nuclear events.

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BIOGRAPHY

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