Virtual Reality for HAZMAT Decontamination Facility Training: An Initial Case Study

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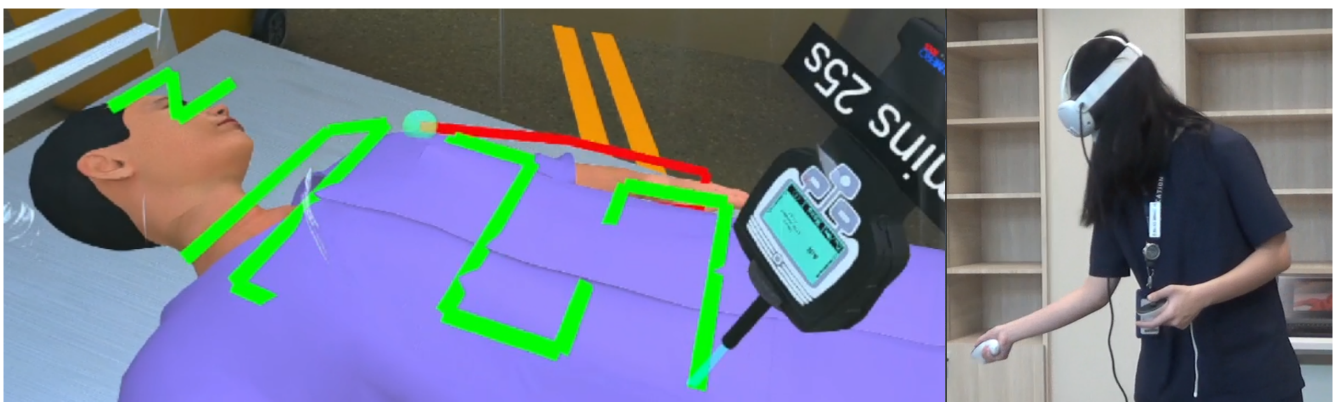

(a) VR Casualty scanning (b) Actual participant

Figure 1: Junior doctors training in VR on decontamination scanning procedure with assessment

Abstract

Mass decontamination training is critical for hospital staff to effectively respond to large-scale chemical or radiological emergencies. Conventional training methods, which involve on-site simulations in open decontamination facilities (ODFs) are resource-intensive and time-consuming. To address these challenges, a virtual reality (VR) system was developed to simulate decontamination workflows, casualty scanning, and prioritization under emergency conditions. This VR platform offers an interactive, modular and process-oriented approach to training. A mixed-methods evaluation was conducted, comparing VR-based training with conventional approaches. Quantitative analysis revealed no statistically significant difference in knowledge outcomes between the two groups, suggesting VR may be as effective as conventional training. Qualitative findings highlighted participants' preference for VR due to its flexibility, streamlined resource use, and immersive learning experience. This demonstrates the potential of VR as a cost-effective, scalable supplement to conventional methods. The findings advocate for a hybrid training approach, integrating VR to enhance knowledge retention while preserving physical training.

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CCS Concepts

• Human-centered computing → Empirical studies in interaction design; **Interaction design**;

Keywords

virtual reality, hazmat, decontamination, training, evaluation study

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1 Introduction

Decontamination involves removing or neutralizing hazardous substances (HAZMAT) from chemically or radioactively contaminated casualties [6]. To ensure hospitals and emergency departments (EDs) are sufficiently prepared for such situations [9], regulations are implemented requiring training and preparation of hospital personnel to respond to such large scale emergencies.

In Singapore, all hospital personnel are required by regulation to undergo mass decontamination training every two years to ensure maintenance of competency [23]. The Tan Tock Seng Hospital has an Open Decontamination Facility (ODF) as the primary decontamination site. Physical on-site training involves disrobing and scrubbing casualties, distributing supplies, scanning for remaining chemicals, and guiding patients to different locations. Trainees are required to don and doff personal protective equipment (PPE) and conduct the mass decontamination. The current training approach requires classroom lectures and live training sessions that take place over two or three days, posing challenges due to limited resource availability and time. Group lectures sometimes pose challenges for trainers to identify individual mistakes and scheduling of the lectures must accommodate all attendees. Additionally, when the ODF is not used for decontamination, the hospital utilizes it to accommodate patients, posing challenges in conducting live training.

Virtual reality (VR) has already demonstrated benefits in training medical procedures [20], allowing training and practice to be conducted in a safe and cost-effective manner. The majority of these involve individual procedures such as surgery [4, 5], childbirth [17], catheterization [22] or triage [25]. However, process-oriented training incorporating multiple room-scale layouts, process workflow and motor coordination within an emergency situation is less explored. There are also further insights that need to be gathered on how VR can complement existing medical training curriculum.

In collaboration with the Emergency Medicine department of a large tertiary hospital, a VR system was developed to supplement current decontamination training. The VR content focuses on enabling users to practice operating a chemical detector, screening casualties for residual chemical hazards, and directing patients to different zones. The virtual training also familiarizes trainees in the layout of different zones such as the showers, decontamination and recirculation areas. It also simulates acute events such as patient seizures and collapse, and allows trainees to understand the prioritization in resolving these situations.

In addition to understanding the learning outcomes and knowledge gained from this VR training, the team seeks to also understand the nuances of the experiences of incorporating VR and how it can complement existing training. The research questions can thus be framed as the following:

- **RQ1** How does training in VR affect the learning outcomes in terms of knowledge in decontamination scenarios?
- **RQ2** What are the experiences of healthcare professionals using VR to train decontamination procedures that take place in a decontamination facility within a hospital?

An empirical study was conducted with 73 medical personnel at a large tertiary acute-care hospital to explore the effectiveness of the usage of VR. The contributions of the paper are:

(1) An empirical evaluation with medical personnel at a large tertiary hospital, comparing the VR system with conventional training methods, specifically in emergency mass decontamination procedures. Knowledge scores suggest that VR might be comparable to conventional training and that one training method is not always more effective than the other.
(2) A qualitative evaluation via semi-structured interviews with medical personnel to provide insights into the experience of learning process workflow, and acquiring skills that require psychomotor coordination. Factors affecting VR training design and implications for VR complementing conventional training were explored.
(3) Details on the design of the VR system and specific key features, including requirements and translation of classroom material and process workflow into VR content.

Compared to the initial version of the VR system [15, 24], the primary focus of this paper is the comprehensive empirical study including both the quantitative and qualitative evaluation, which is the main contribution of the paper. In addition, this work substantially refines and extends the VR system's design, specifically integrating functionality for showering simulations, acute event handling, walker casualty scenarios, and graphics, and details the modular architecture.

2 Related Work

Many applications of VR have been used in the healthcare context to enhance staff training and improve performance in various medical procedures [8]. These training programs typically focus on specific roles, such as simulations for nurses practicing urinary catheterization [12], childbirth and delivery [17], ambulance bus training for equipment familiarization [13], and a trauma simulator for medical students to make diagnoses and decisions based on equipment measurements [10]. Most medical training simulations are typically confined to a defined area, with minimal physical movement required from trainees.

Several VR training applications outside the healthcare sector have demonstrated the utility of virtual environments for skill development in high-risk scenarios. Examples include training military personnel in cordoning areas affected by Chemical, Biological, Radioactive, Nuclear, or Explosive (CBRNE) threats [14] and investigating CBRNE emergencies [1, 11, 19]. Other systems include triage training in mass casualty events [8, 18, 26], and training relief agency staff on the assembly of a rescue platform [21], and a VR training program developed for industrial workers that involve responding to chemical incidents and controlling leaks[2]. There was a small section dedicated to decontaminating equipment and staff [2].

Most VR simulations surveyed provided similar efficacy compared to the live simulation [18]. Although these simulations are still not ready to replace real-life training procedures entirely [16], they could still be complementary to in-person training.

For HAZMAT decontamination training, it necessitates that trainees transport patients across various sections, including triage areas, showering stations, and treatment rooms. Trainees must orient themselves and acclimate to the dynamic configurations encountered during emergency scenarios. Therefore, compared to prior work, simulating multiple areas and movement between rooms could be explored.

3 Design and Implementation

Design process: Using a collaborative and multidisciplinary approach, the team included emergency department physicians (from a local hospital), faculty and engineers from the Infocomm Technology and Health Sciences departments of a local university.

Selected non-medical members of the team attended an in-person conventional decontamination training exercise to understand the content. In the current model of practical training, a classroom briefing is first conducted, before proceeding to the ODF for further practice. Training includes wearing the CLD 500 and C420 PAPR Personal Protective Equipment (PPE), and performing scanning and showering duties on a manikin while being guided by medical staff, and familiarization with the ODF layout, facilities and movement of the trolleys between stations. Brainstorming and consultations with the overseeing staff responsible for the training were then carried out. Based on these insights, the system was designed with the workflow encompassing key stages in assessing decontamination status and casualty prioritization. To bridge the gap between experiencing realistic situations and accessible educational content, the system includes interactive immersive elements to produce more authentic scenario-based learning. This system comprises two modules: learning and assessment. The learning module provides hands-on VR training covering the essential steps of decontamination. The VR-based assessment module evaluates users' knowledge and learning outcomes.

Implementation : The simulation was implemented using Unity Engine 2021.3.9f1, for the Meta Quest 2 Head Mounted Display (HMD). The 3D assets and environment are modeled in Autodesk 3DS Max and Blender to accurately replicate the real-world decontamination training equipment and facilities of the hospital.

3.1 VR-Based Learning Module

The learning module consists of a structured modular design, with the learning objective to screen casualties of various mobility and severity for contaminants. The total time for completion of the entire VR module is approximately 2 hours. The primary goal is to ensure that all casualties undergo comprehensive decontamination to eliminate any residual chemical or radioactive substances. Additionally, users will be taught to thoroughly screen casualties using the ChemPro 100i detector to determine the level of contamination. Users will also learn to assess the severity of each casualty's condition using a chemical detector and to apply a colored wristband according to the screening result. Furthermore, users will receive instructions on managing casualty movement, leading up to the preparation of casualties for scanning procedures.

In this structured modular design, decontamination training scenarios are thus divided into five main stages and 10 sub-stages to ensure progressive and systematic knowledge acquisition, as shown in Table 1 and Figures 2 and 3. The design gradually increases in complexity while allowing flexibility, enabling trainees to reinforce essential knowledge, e.g., during the training the Detector Setup is structured as the first stage, allowing the trainee to learn basic VR operations in a stationary setting, without needing to move around, while the relatively complex Showering stage is structured as a later stage. It balances cognitive load and knowledge retention. Additionally, a beginner tutorial is offered to familiarize users with navigation and interaction techniques within the virtual space. The stage details can be found in the Appendix.

3.2 VR-based Assessment Module

After completing the learning module, users are required to participate in a VR-based assessment. The assessment follows the decontamination workflow, as illustrated using arrows in Figure 2. The actions performed by users for each casualty are tracked and displayed upon completion of the assessment (Figure 4 (b)). The detector setup and prioritization are potential challenges where users are guided if they encounter difficulties.

Training in the scanning process is crucial, as all parts of the casualty's body and limbs needs to be systematically scanned in a certain path from the head to the feet, in order to detect contaminants. During the scanning process, the system records the scanning path as users scan each casualty, storing it as an image file shown in Figure 4 (a). The system evaluates if a person's head is scanned first, followed by the limbs in any order. Instructors can then review the image file to determine if the scanning pattern aligns with the intended sequence. Additionally, the system measures the time taken to scan each side of the casualty to ensure compliance with the minimum and maximum required scanning times. The timer initiates when the detector identifies the head and concludes once all four limbs have been scanned. Compared to conventional training, this approach simplifies and enhances the assessment process, reducing manual effort and minimizes the likelihood of errors.

4 Evaluation

A between-subjects, mixed-methods study was conducted to gather insights into participants' experiences and perceptions of learning in a VR environment. A paper-based (a) knowledge questionnaire was administered to both groups of participants to evaluate their knowledge of concepts. Additionally, VR participants completed the (b) Flow Short Scale (FSS) [7] and participated in a (c) semi-structured interview. The FSS intends to measure the subjective

Stage	Sub-stages	Type	Scope
1	A	Detector Setup	Learn how to assemble and operate the chemical detector
2	B&D	Casualty Scanning	Learn the process of screening walking and trolley casualties for nerve agents, and how to manage casualties after scanning based on their level of contamination
3	C&E	Prioritization	Learn to interpret the triage card and process of prioritizing walking and trolley casualties accordingly when multiple casualties are present
4	I	Showering	Learn to disrobe, shower, and re-robe casualties
5	F-H&J	Acute Events	Learn to handle acute emergencies such as patients experiencing sudden deterioration, nerve agent-induced seizure, and "Code Black"

Table 1: The VR learning module with five main stages.

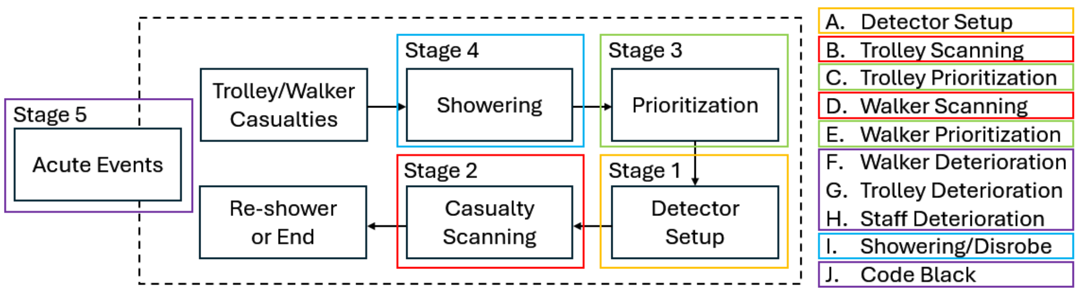


Figure 2: The arrows indicate the decontamination workflow. Modular learning stages and substages are boxed to structure the training process. The tutorial (sub)stages are designed to emphasize essential knowledge while gradually familiarizing trainees with VR.

(a) Detector setup (b) Casualty scanning (c) Prioritization (d) Showering (e) Acute event: seizure

Figure 3: Stages in decontamination training

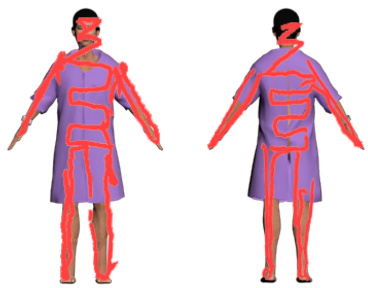
experience of being in a state of flow, where a person is fully immersed in an activity and experiencing intense focus. Thematic analysis [3] was conducted on the interview data to explore participant perceptions of training in VR. The study is approved by the Domain Specific Review Board (DSRB) of the hospital.

A total of 73 participants (14 male, 59 female, 0 non-binary, with a mean age of 29.23 years) were recruited, consisting of junior doctors termed as medical officers (MOs), nurses, and other medical professionals from a large acute-care tertiary hospital. All the participants had never undergone decontamination training. Of these, 45 participated in conventional classroom training while 28 underwent VR-based training.

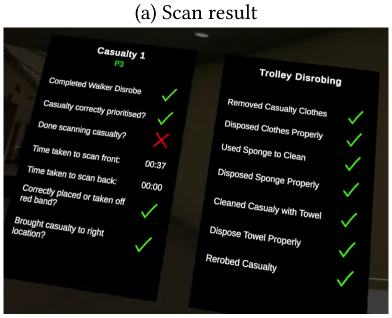
4.1 Quantitative Results

The post-training knowledge questionnaire included "True/False" questions that focused on participants' understanding of handling emergency protocols and the relevant materials covered in both physical and VR training groups. They aligned closely to the test questions administered in the conventional classroom setting. The questionnaire was reviewed by emergency physicians at the hospital.

The results from the knowledge questionnaire were tested with the Levene's test. The Levene's test was significant, indicating unequal variances between the group that underwent traditional ED training (conventional) and the VR group. Hence, a Welch t-test was performed to determine if there was a statistically significant difference between the two groups. The t test indicated that the difference between participants in the conventional group (M=74.97, SD=6.65) and the VR group (M=70.46, SD=14.10) was not statistically significant ($t(34.569) = 1.5873$, p-value = 0.1216), suggesting insufficient evidence to conclude that one training method is more effective than the other.



(a) Scan result



(b) Sample overall assessment output

Figure 4: VR assessment

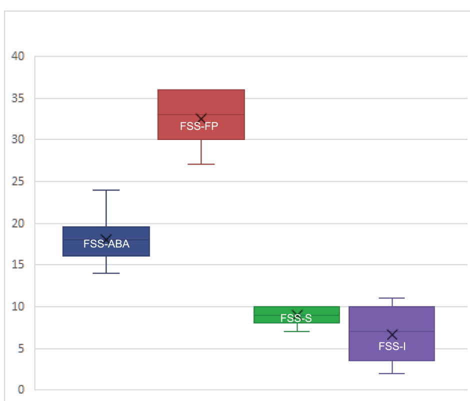


Figure 5: FSS results.

As shown in Figure 5, in the FSS-ABA category, fair levels of absorption were observed which indicated participants were perceived to be absorbed in the activities and experienced pronounced sense of flow, leading to good fluency. The higher levels in FSS-FP demonstrated the participants' great fluency in performing the tasks, signifying a degree of immersion and automaticity. The lower levels of FSS-S align with the levels of absorption that demonstrated decreased self-consciousness that are usually observed during flow states, and finally the low intensity found in the FSS-I category suggested that participants reported a less pronounced intensive experience during the session.

4.2 Qualitative Findings

Two authors contributed to the qualitative data analysis and write-up. Having differing backgrounds in computer science and healthcare, this team complemented each other in the co-creation of themes [3]. Three overarching themes related to participant perceptions of VR training emerged from the data: 1) VR as a viable and preferred alternative to traditional training, 2) Streamlined and sustainable use of resources, and 3) Dichotomy of advantages and pitfalls. A brief overview of the themes are presented below:

VR as a viable and preferred alternative to traditional training

Most participants found VR training to be a viable and preferred alternative to traditional one. They mentioned how VR addresses the limitations of traditional emergency training while enhancing the overall learning experience. Participants reflected that there are "no time pressures," and they can "learn at their own pace" with "minimum supervision" in VR. They reinforced that they can engage with scenarios as much as they want. Whereas in traditional training, there are time pressures in training as a group, which results in insufficient time to review all the learning materials.

"... it's quite simplistic... and it was quite efficient to get everything covered within the time limit cause in real-life I think it will take much longer..." - Participant 3.

In addition to being able to pace their own learning, participants expressed that the VR training was structured sequentially with clear instructions that helped guide them towards achieving module objectives.

"After a while, I think towards the end, [I] sort of know how to do the scanning pattern, and then the whole flow of events. The way it was structured, it was quite sequential, it's easy to understand everything." - Participant 16

This faster and more efficient way of learning emergency hospital procedures also saved time for training staff and instructors. Participants could work through modules independently without the need to ask instructors questions that may hold up a group.

Streamlined and sustainable use of resources

A substantial allocation of resources in terms of time, personnel, and consumable waste was required for traditional training. Participants shared that VR training helped streamline efficiencies in terms of physical preparations and scheduling. Patients who would be occupying the ODF during non-training days would not need to be relocated.

"In the ODF, it is operational everyday. [VR] will be helpful in the long run, as you do not have to shut down the entire [ODF], and not having to think of where or how to shift the patients, and re-organize everything." - Participant 2.

Participants conveyed that further logistical preparations that need to be completed within a limited time frame, such as disconnecting medical equipment to prevent electrical hazards, would no longer be necessary.

Some also expressed that VR training also helped alleviate staff shortages in departments when doctors, nurses, and volunteers were required to accommodate a full day of training. A full day is not required with VR training because it eliminates the need for starting with a slide-style lecture that takes place outside of the ODF. In turn, VR gives users a better understanding of what the ODF looks like in emergency situations. Finally, participants highlighted that VR training eliminates the need for disposable consumables, significantly reducing waste and promoting a more sustainable training process.

Dichotomy of advantages and pitfalls

Although participants initially faced challenges in adapting to the VR controls, they were able to quickly familiarize themselves and complete the training session successfully. This adaptability was facilitated by what they reported as a "comfortable training environment", which was a room designed to induce calmness and enable participants to think logically and focus on the task at hand. Participants also appreciated the positive experience of conserving energy by using VR teleportation mechanics rather than walking within the ODF.

However, participants also pointed out that a lack of "ambience" in the VR scenarios contributed to them feeling a lack of "urgency." The serious tone and intensity of emergency situations undergoing mass contamination was absent.

Aside from the lack of urgency, participants found aspects of VR training to be more realistic than in-person training due to the hands-on engagement and seeing the ODF in it's emergency situation state.

"I know how the ODF looks like, but I don't know how it looks like in a situation whereby there are mass casualties, so it does help me to visualize on how the layout would be like… ." - Participant 18

Overall, participants expressed a strong interest in the integration of VR into emergency training for reasons mentioned in the three themes above. Several participants emphasized the importance of integrating physical practice with VR training. They reported that while VR provided a valuable learning platform, they did not feel that VR could not completely instill the confidence they need in real-world practice. This underscores the need for a hybrid approach that combines virtual and physical training to ensure learners feel adequately prepared for real-life emergencies.

5 Discussion

Virtual reality technology enables repeated practice, modular training, and exposure to challenging workflow that takes place in several locations, which is widely recognized as a crucial factor for skill retention. The ability to simulate similar scenarios multiple times allows learners to refine their techniques, address mistakes, and develop a stronger procedural memory. Despite this advantage, when participants were asked how to further improve their confidence level, the most common response is the opportunity for a physical practice session of the scanning procedure or, at minimum, an interaction with the physical scanning device.

Participants also consistently expressed that their confidence in understanding the room layouts could be further enhanced by incorporating a physical practice component. Gaining a comprehensive understanding of how the actual ODF is structured during the physical practice would enable learners to draw parallels with the simulated emergency environment in VR. This alignment could assist learners to become familiar with the setup of the ODF environment. While suggestions were made to include arrows and signs to guide participants in navigation, physical exploration of the area was still preferred for developing deeper familiarity and confidence. The most common suggestion involved opportunities to engage in hands-on practice sessions.

Both sets of feedback highlight a gap in the VR training experience: while it effectively teaches procedural knowledge and situational responses, it may not fully replicate the urgency, and the tactile physical interaction required in real-world scenarios. The importance of physical practice lies in its ability to bridge the gap between theoretical knowledge and practical application. Interacting with physical equipment would allow learners to build confidence in handling the device, once they become familiar with its weight, texture, and functionality, which reduces hesitation and errors during real-life use.

Moreover, the combined approach of integrating VR-based repetition with physical practice may cater to diverse learning styles. For instance, kinesthetic learners can benefit from direct interaction with objects instead of digital simulations alone. By blending the virtual and physical components, training programs can provide a more holistic learning experience. These benefits were also attributed to the high levels of engagement and flow states experienced during the training, which allowed participants to immerse themselves fully in the learning process.

6 Conclusion and Future Work

With collaborative effort from the Emergency Medicine department of an acute-care hospital, a VR decontamination training system was developed to enhance emergency preparedness. The system allows users to practice decontamination processes including showering and using a chemical detector device to scan casualties for chemical hazards. Additionally, users can experience unexpected events that may occur while performing their primary duties and learn how to maneuver through those situations. A user study involving 73 medical professionals was conducted to evaluate VR's learning outcomes and experiences. No significant differences in knowledge outcomes were observed between conventional and VR groups. VR participants expressed high absorption and flow. Therefore, VR can serve as a valuable complementary learning tool.

Future evaluation studies could include conducting quantitative comparisons with existing methods, recruiting more balanced participants, using more sensitive assessment tools, and exploring both long-term retention and real-world skill transfer via longitudinal studies. Additionally, integrating physical or haptic elements may help replicate the tactile and urgent dimensions of real-life emergencies.

Another potential enhancement is using machine learning methods for intelligent and authentic training and assessment methods while augmenting the overall user experience. For instance, deep learning-powered computer vision methodologies could be utilized to analyze and assess the scanning image's content (Figure 4 (a)). Additionally, gamification elements could be incorporated to improve learning retention and engagement. Future iterations will aim to simulate and implement the entire decontamination training process within the VR environment, further advancing the realism and educational value of the system.

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A Appendix

A.1 VR-Based Learning Stages

A.1.1 Detector Setup (Stage 1). In this stage, the aim is to first learn to operate the ChemPro100i chemical detector device, inclusive of switching caps and holding down the power button to prepare it for scanning. This is done by holding the protective inlet cap, which detaches the cap from the detector's body, then proceeding to attach both the monitoring cap and the probe by bringing them close in a simplified twisting motion, enhancing psychomotor precision.

A.1.2 Casualty Scanning (Stage 2). The main objective is to assess the severity of a casualty's condition through the scanning procedure and ensure they are delivered to the appropriate destination for treatment. Users learn how to scan both the front and back of a patient using the device, adhering to the zigzag pattern. Casualties who are unable to walk independently or are unconscious will be placed on a trolley and referred to as *trolley casualties*.

Red wristbands are applied to the casualty if nerve agents are detected, regardless of their consciousness. The red band signifies a need for immediate medical intervention, indicating a high level of contamination. Walking casualties with detected nerve agents will be escorted to designated sections for further decontamination, while trolley casualties will be wheeled. Users wheel trolley casualties by grabbing the push handles and moving them to their destinations. It is crucial that neither the detector nor the user come into direct contact with the casualty.

The destination for a casualty is determined based on the scan results, either the Radiation Scan Station (RSM, end of the workflow) or the decontamination shower area again. Casualties may require multiple rounds of scrubbing depending on the level of contamination.

A.1.3 Prioritization (Stage 3). The objective is to prioritize casualties with the most severe contamination status. The casualty waiting queue is dynamically changing, as users need to compare the casualties' status by checking the treatment triage card and observing if a red wristband is attached to determine the priority. Each casualty has a priority level indicated on the triage card, e.g., the priority order from high to low is: P1 with a red wristband, P1, P2 with a red wristband, P2, P3 with a red wristband and finally P3 as determined by the screening result.

A.1.4 Showering (Stage 4). The showering stage guides the process of disrobing, showering, and re-robing the casualty. During disrobing, valuables like wallets and phones are placed in a tagged, sealed bag, then clothing is removed. The bag and clothing are put into respective bins. In the shower lane, water runs for 15 minutes while staff use a sponge to clean the casualty. The casualty is then moved to the re-robing area, where they are dried with a towel before being dressed in a bathrobe and blanket. The used sponge and towel are disposed of for safety.

A.1.5 Acute Events (Stage 5). In this stage, the focus is on learning how to manage casualty emergencies, such as seizures induced by nerve agents or patient deterioration, and taking appropriate action. In these situations, the casualty will be isolated, the emergency button activated, and a physician notified immediately to provide necessary care. During "Code Black," users managing casualties must exercise caution upon identifying an imminent threat, and must respond appropriately by following established protocols. This includes informing the commander before evacuating, and attempting no further action unless instructed. Users must then efficiently navigate towards the exit when signaled to allow relevant personnel to address the situation effectively.