Virtual Advancement of Learning for Operational Readiness: Implementation and Transition of a VR Medical Simulation Capability for TCCC Responders

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ABSTRACT

Introduction. High-fidelity medical simulation training is one of the few evidence-based interventions demonstrated to reduce medical errors and improve trainee readiness for medical techniques, tactics, and procedures. However, limitations of current simulation technologies limit immersive simulation capabilities for the prehospital setting, due to limitations in their capability to represent realistic casualties and the psycho-environmental characteristics of battlefield environments. In this paper, we report our adaptation of a commercially available civilian virtual reality (VR) medical simulation training platform for use in a novel curriculum for medical sustainment training of USAF Pararescuemen and other special forces personnel.

Methods. First, we performed a needs and gaps analysis, providing a roadmap for the agile, interactive development of the simulation training curricula. Next, we specified and implemented the required capability using a layered framework, with an underlying capability platform layer for DOD virtual reality medical simulation training adapted from the prior civilian capability, and a curricular layer developed on top of the platform using a domain-specific language, and interpreted in the platform runtime. Finally, we deployed the resulting capability, starting with a small-scale test and evaluation period and proceeding to a large-scale distributed evaluation period before beginning the programmatic transition for long-term procurement and sustainment.

Results. Five major training areas were identified for this project: TCCC, PCC, SUC, CBRNE, and certification readiness. Six design principles were identified to mitigate drawbacks of previous VR medical simulation efforts: 1) Full Immersion, 2) Multiplayer First, 3) Psycho-environmental Realism, 4) Dynamic Physiology, 5) Complete SKOs, and 6) Mutable Scenarios. A 25-scenario curriculum was successfully developed after the adaptation of the civilian simulation training platform with DOD feature requirements. The resulting curriculum (VALOR CORE) underwent phased deployment and then began the programmatic transition.

Conclusions. Here, we report on a successful multi-year collaborative effort between industry, academia, and the US Air Force to develop a mission-ready VR medical simulation capability that uses low-cost, commercially available technology and addresses shortcomings that previously limited the utility of such virtual simulation training. Overall, we have demonstrated that VR medical simulation can be a practical, usable tool within the DOD and that current-generation technologies can be leveraged to produce training capabilities that can solve mission needs now, even as new technologies (such as advanced haptics and full-body sensory immersion) are under development.

ABOUT THE AUTHORS

Karthik V. Sarma PhD is co-founder and Chief Technology Officer at SimX. A computer scientist with extensive experience in healthcare, bioengineering, health policy, and virtual reality, Karthik is a leading expert in virtual reality training and simulation. In addition to receiving multiple awards and authoring many peer-reviewed works, he has been the recipient of a wide variety of grants to support research efforts in medical simulation training. He is the Principal Investigator of the DOD-funded Virtual Advancement of Learning for Operational Readiness (VALOR) program and received his undergraduate training in computer science from the California Institute of Technology and his doctoral training from the UCLA-Caltech Medical Scientist Training Program.

Michael G. Barrie MD is Medical Director for Special Projects at SimX. He has extensive experience in medicine and medical simulation training through his role as a board-certified emergency physician, and his academic work as faculty at The Ohio State University before joining SimX. He previously served as an academic medical educator and a DHA grant-supported investigator and has published academic works and talks in the area of innovation in medical education. He is the primary clinical instructional designer for AFSOC simulation training for the VALOR program, with a focus on TCCC training for USAF pararescuemen and special operations surgical teams.

COL John R. Dorsch DO, USAF (ret.) is Senior Military Advisor at SimX. He is a former USAF Colonel, Chief Flight Surgeon, and Board-Certified Emergency Medicine Physician with an exemplary military/academic record, years of combat trauma and field medical experience within SOF/CSAR, and expertise in medical technology innovation. Col Dorsch (Ret.) was previously the wing surgeon, physician, and medical officer for the 24th SOW, where in addition to his duties, also fostered numerous innovation projects in the Special Warfare community, including innovations that transitioned into Programs of Record, as the Senior Medical Advisor for Air Force Special Tactics of over 2000 personnel and also the Air Force Pararescuemen (PJ) Medical Director (700+ PJs). He also served as a voting member of the Committee on Tactical Combat Casualty Care, and has deployed numerous times in support of DOD operations around the globe.

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Ryan J. Ribeira MD MPH is the founder and Chief Executive Officer of SimX, Inc., and Assistant Professor of Emergency Medicine at Stanford University. Since founding the company, Ryan has led SimX from product ideation to market success. Under his leadership, SimX has attained the market-leading position in professional-grade virtual reality medical simulation training and become the standard for VR simulation at a variety of prestigious institutions in the United States and around the world. He is a sought-after speaker on medical simulation, and has spoken at TechCrunch Disrupt, the International Meeting on Simulation in Healthcare, the Tech+ Forum, and many more.

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1. Background and Problem

Figure 1. USAF PJs conduct in-flight medical simulation training using standardized patients. USAF image by SSgt Rito Smith. The appearance of U.S. Department of Defense (DoD) visual information does not imply or constitute DoD endorsement.

In future all-domain combat operations against near-peer competitors, the effort to maintain the "Golden Hour" (by providing definitive care within 60 minutes of sustaining traumatic injuries) is likely to be overwhelmed by casualty counts incurred from the use of highly effective weaponry employed by nations on a scale not seen in recent decades. Achieving optimal survivability and recovery under combat situations requires training a significantly larger proportion of warfighting personnel in stabilizing and temporizing medical techniques and protocols to extend the "Golden Hour" for as long as possible (Riesberg et al., 2017). This new requirement for Prolonged Casualty Care (PCC) will require significant training across a wide range of military personnel to maximize the availability of PCC-trained personnel at the point of injury (Remley et al., 2021). Providing such time and material-intensive medical training is impractical with today's commonly employed training methodologies, but emerging extended reality (XR) training capabilities will enable far wider dissemination of life-saving training, which can enable the scaling necessary to save the lives of combat casualties.

Medical simulation training (MST) has rapidly become a critical component of the initial training and sustainment of knowledge, skills, and abilities (KSAs) across the spectrum of care. MST is one of the few evidence-based educational interventions that improve the quality of care, reduce medical errors, and lead to improved outcomes (McGaghie et al., 2010, 2011). A wide variety of modalities for MST are in routine use, ranging from "tabletop" paper-based simulation, low- and high-fidelity manikin-based simulation, full mission profile field exercises, screen-based computer simulation, and virtual and augmented-reality based simulation. Simulation-based training has achieved widespread subjective acceptance and has a significant and growing rigorous base of evidence supporting its efficacy in training, with many states in the United States now allowing up to 50% of required civilian clinical training hours to be performed using simulation (Crowe et al., 2018; Roberts et al., 2019).

Given the high cost and logistical complexity of full mission profile exercise training, the majority of medical simulation training today is performed using manikin-based and paper-based simulation. Manikin-based training is a powerful tool that can enable learners to practice challenging tactile skills under pressure, with some of the most advanced manikins available today allowing for the simulation of selected measurable autonomic physiologic processes, advanced wounds and hemorrhages, and other traumatic injuries.

However, physical manikin simulators are technologically limited in their ability to provide high fidelity, immersive education. They are generally available in limited sizes and shapes, are immobile, bulky, and static, and have significant limitations in their interactivity; for example, a manikin will never writhe during a critical procedure to any realistic degree. In addition, manikin-based simulation is not a conducive modality for providing the psychosocial and environmental elements of military medical practice that are essential to truly immersive training, such as bystanders (family members, local nationals, etc.), environmental dangers (enemy action, weather considerations, etc.), patient distress (pain, vocalizations, etc.). They also lack a significant range of motion and degrees of freedom in the main joints, are difficult to transport, and require synchronous, collocated training, significantly limiting their scalability and utility (Barrie et al., 2019; Ghoman et al., 2020; Pears et al., 2020).

Virtual reality (VR) medical simulation training is a rapidly growing modality for MST (Barrie et al., 2019; Izard et al., 2018; Sapkaroski et al., 2019). VR simulation training has several benefits over manikin, screen-based, and paper-based simulation, including significantly reduced cost and logistical complexity versus manikin simulation, enhanced medical and psycho-environmental realism, and easier direct, automated measurement of learner performance (Frederiksen et al., 2020; Lebdai et al., 2021; Lohre et al., 2020; McGrath et al., 2018; Peng et al., 2021; Rushton et al., 2020; Semeraro et al., 2019; Yu et al., 2021; Zackoff et al., 2020). However, VR simulation training has historically been limited by several key barriers: 1) VR simulation training often made use of non-realistic elements, such as buttons, drop-down menus, and selectors, which negatively impacted realism and immersion, 2) VR simulation training often required individual scenarios to be built "from scratch," limiting the breadth of training use cases, and 3) VR simulation training suffered from poor learner and educator acceptance due to the need for complicated, tethered hardware systems and poor application system usability (Massoth et al., 2019; Rochlen et al., 2017).

Figure 2. USAF PJs training with the developed VALOR CORE VR medical simulation capability on exercise at Fort McClellan ANG Training Center. The appearance of U.S. Department of Defense (DoD) visual information does not imply or constitute DoD endorsement.

Here, we discuss the development, field testing, transition, and deployment of a next-generation VR medical simulation training system for TCCC Tier 4 providers: the VALOR CORE curriculum. This system was designed and implemented to directly address previous limitations of VR MST, including: 1) by focusing on immersion and realism, 2) by using a platform model for implementation to enable low-cost development and iteration of training content, and 3) by making use of commercial all-in-one wireless VR systems which are easy to use, require a minimum of setup time, and allow room-scale untethered operation.

2. Design and Technical Approach

The methodology for this effort followed the Analysis, Design, Development, Implementation, and Evaluation (ADDIE) model for instructional design and development, with each phase receiving input from VR engineers, instructional designers, clinical subject matter experts, and military subject matter experts.

Needs Analysis and Design Principles. In the initial phase of the project, an analysis of training requirements and gaps for TCCC Tier 4 providers was conducted, with a focus on US Air Force Combat Rescue Officers (CROs) and Pararescuemen (PJs). An interprofessional clinical educator working group was formed, consisting of the emergency physicians, emergency medical technicians, emergency physician assistants, registered nurses, USAF PJs and CROs, and the USAF Pararescue Medical Director, who collaborated on needs analysis and initial curricular design.

Once the learner population was identified, a scenario and environmental design for the proposed curriculum was created, making use of the needs analysis as well as the USAF Pararescue Operations Handbook (Shackelford et al., 2021) and the appropriate Joint Trauma System (JTS) Clinical Practice Guidelines (CPGs). Specific learning goals for each curricular scenario were identified, with cross-references to appropriate tactics, techniques, and protocols (TTPs). Additionally, the working group developed a set of design principles for VR scenario implementation, based on identified limitations in prior virtual medical simulation efforts, which were then used to guide further stages of the process.

Hardware Selection. Hardware selection for this project was driven by a variety of competing interests and requirements. Full-scale realism in training requires the adoption of a “tetherless” approach to enable collocated multi-trainee operation in room-scale medical environments. Simultaneously, hardware must be capable of rendering and displaying dynamic content with a sufficient degree of realism to enable positive skills transfer during training. These requirements must also be balanced with government procurement regulations (such as the US Trade Agreements Act and Section 889 of the 2019 National Defense Authorization Act), which exclude most current consumer-targeted COTS VR hardware.

Due to these considerations, as well as the reality that the hardware field is evolving continually, with new options often released and frequent COTS new market entrants, the choice was made not to select a specific hardware platform, but instead to develop the curriculum on a platform-agnostic basis with testing performed on a representative demonstration platform which met capability requirements as well as regulatory requirements. The selected demonstration platform was the HTC Focus 3 based on the Snapdragon XR2 chipset.

Figure 3. CASEVAC Prolonged En-Route Care with POC Field Ultrasound in VALOR CORE.

Implementation of Platform and Curricular Layers. Implementation of specified requirements proceeded using a layered approach. An underlying platform model was adapted with requirement-specific medical simulation capabilities (such as tools, interventions, sets, kits, and outfits, interactions, etc.) and served as the foundational platform layer. A curricular layer was then produced using a scenario domain-specific language (DSL) to produce the required scenario content for the curriculum. Produced DSL specifications for each scenario were then interpreted at runtime by the VR engine using the platform layer, thus allowing for rapid iteration and modification of scenarios, as well as rapid production of each additional scenario.

During the specification phase, concept specifications were first developed for each proposed scenario by the clinical instructional design team, detailing the content overview, components, and medical context. Concept documentation was then iterated upon in collaboration with clinical and military SMEs until mutual agreement was reached. Then, during technical specification, each item had learning objectives, scenario state flows, medical assemblages and equipment, psychosocial, and environmental factors specified, again with iteration by the clinical instructional design team in collaboration with specific military SMEs. Iteration was continued until the specifications were finalized by mutual agreement. Finally, the technical scenario production team developed implementation engineering design documentation to facilitate implementation and production by the VR implementation team. This documentation included both feature documentation for the platform layer as well as scenario domain-specific language documentation for the curricular layer. This scenario engineering documentation included production of patients and non-player characters with dialogue, animations, appropriate vitals and physical findings, scenario engine state flow and associated events and triggers, environmental state flow, VR interactions, learning objectives and assessments, scenario-specific facilitator controls, medical interventions and events, and appropriate in-scenario medical documentation, records, procedures, and laboratory findings. All produced engineering documentation was then used by the scenario implementation team to produce, test, and iterate the scenario curriculum until both the quality assurance and military SME teams were in concurrence with finalization.

3. Outcomes

Curriculum Selection. After conducting the training requirements needs and gaps analysis, the working group selected five major areas for curriculum development: Tactical Combat Casualty Care (TCCC), Prolonged Casualty Care (PCC), Small Unit Care (SUC), Chemical, Biological, Radiological, Nuclear, and high Explosive (CBRNE) response, and certification readiness. Based on these major curricular areas, a specific scenario curriculum was designed by the working group with key scenarios in each area, such as Combat Mass Casualty (TCCC), Transport Ventilator-Associated Pneumothorax (PCC), Dive Medicine/Arterial Gas Embolism (SUC), Organophosphate Poisoning (CBRNE), and ACLS Megacode (certification readiness). A total of 25 scenarios were produced for the CORE curriculum based on these specifications.

Design Principles. The working group identified several key design principles which were used during the specification and implementation phases of the project. These design principles were intended to enable advancing the field of VR medical simulation by creating novel solutions to limitations that remained unsolved by previous efforts. These design principles included:

Figure 4. TCCC Mass Casualty Simulation within the VALOR CORE curriculum.

1) Full Immersion: the developed system must require users to interact with the simulation in the same manner that they would in a real clinical environment; no buttons or menus are permitted, and users must physically move their hands to pick up and use items in appropriate locations to achieve the simulated effect.
2) Multiplayer First: the developed system must allow for multiple providers to work together in the same way that they would in a real clinical environment, including being able to see and hear each other, and collaborate on administering care (i.e. two-person resuscitation, etc.).
3) Psycho-environmental Realism: the developed scenarios must include the psycho-environmental factors found in the real practice environment (i.e. they must include bystanders, walking wounded, background noises, hazards and enemy action, etc.).
4) Dynamic Physiology: the developed scenarios must reflect dynamic patient physiology, with learner actions and non-actions leading to physiologically appropriate changes in the patient state over realistic time periods.

5) Complete SKOs: the developed platform must support the full sets, kits, and outfits (SKOs) that are carried into the field by providers and allow learners to use these SKOs in the full multitude of appropriate choices that they might in the field, rather than limiting to only specific intervention selections.
6) Mutable Scenarios: the developed platform must not require scenarios to be "hard-coded" into the system, but instead must allow scenarios to be tweaked as reasonable to adjust learning objectives and other key dynamic scenario factors based on the evolution of clinical practice over time.

Test, Deployment, and Sustainment. A phased deployment strategy was employed to iteratively refine the system and fine-tune the deployment methodology. The system was first deployed for initial test and evaluation at a single USAF Pararescue training site for evaluation by an AFSOC Special Tactics Squadron. After successful completion of the test and evaluation period, feedback regarding usability and deployment needs was collected and integrated into the deployment methodology; in particular, enhanced offline capabilities were integrated to allow for easier usage of the system during training in austere locations. Next, the test and evaluation deployment was expanded across 12 USAF Pararescue sites, as well as two sites within the DHA for additional testing and evaluation. During this phase, feedback was also collected regarding any additional capability gaps and training needs; this feedback was used to direct additional ongoing curriculum development work (see Section 4). After successful completion of the expanded test and evaluation period, the capability was released for general availability for procurement within the DOD, with several dozen additional sites added. The project then began advancing towards initial operational capability with the development of MAJCOM requirements and Program of Record transition.

4. Ongoing Work

Figure 5. Field intubation of a blunt force trauma casualty within the VALOR CORE curriculum.

Extended CORE Curriculum. Based on training needs identified during the test and evaluation phases, an extended TCCC Tier 4 provider curriculum was designed by the working group. This curriculum extends the initial CORE content described in the work above, including additional scenarios tailored towards specific training needs representing low frequency, high yield medical management situations. These specific foci include field ventilator management, hypothermia, orbital compartment syndrome, extrication, and an expanded small unit care curriculum. These additional 14 scenarios are currently in the development phase.

Simultaneous Multi-Role Training. Another identified major gap in current training capabilities is simultaneous multi-role training, in which casualties are treated and handed off across the roles of care from the point of injury, to MEDEVAC, to the MTF where definitive treatment can be provided. A simultaneous, multi-role training platform capability and scenario is in the development phase. This capability allows multiple teams (which may be physically co-located or distributed) to participate in the same scenario simultaneously, be located at different virtual locations and move between them (i.e., a MEDEVAC helicopter transport with a Pararescue team landing at the POI), and transload patients between teams while performing all required medical care.

Advanced Resuscitative Care. A scenario curriculum is in development focused on two major life-saving interventions targeted at noncompressible torso hemorrhage (NCTH): the massive transfusion protocol (MTP), and resuscitative endovascular occlusion of the aorta (REBOA). These new interventions are now part of the TCCC-ARC skillset, and the resulting curriculum is intended to enable faster sustainment of these capabilities through training across a variety of battlefield casualty scenarios, such as junctional and airway wounds and severe blast injuries.

Veterinary Medicine. Training for the provision of care to wounded animals by non-veterinary healthcare providers is another identified major gap in current training. A curriculum is in development to assist in skills transfer for field assessment and stabilization of commonly encountered conditions, such as acute trauma and gastric dilatation-volvulus.

Prospective Controlled Test and Evaluation. Though VR medical simulation training already has a significant body of supporting evidence of efficacy (see Section 1), few randomized controlled trials (RCTs) of efficacy have yet been performed. A multi-site, prospective RCT including military and civilian trainees evaluating VALOR scenarios is currently in progress, with subject recruitment planned for late 2022. This RCT will compare VALOR VR medical simulation scenarios to the current standard of practice training approaches (such as lecture or paper-based training and HFMS). Study outcomes measured will include user acceptance, system usability, educational efficacy, and cost.

5. Discussion

In this paper, we report on a multi-year collaborative effort between industry, academia, and the U.S. Air Force to develop a mission-ready VR medical simulation capability that uses low-cost, commercially available technology, and which addresses shortcomings that previously limited the utility of such virtual simulation training. This effort spans the design, specification, engineering implementation, pilot testing, and transition to procurement and sustainment of the capability.

During the project, several challenges were encountered and overcome to escape the “Valley of Death” – the well-known phenomenon of successful research programs which never end up in the hands of warfighters. In particular, innovation was required around the particular challenges of real-world defense training, such as the need to operate technology in austere environments, the absence of dedicated simulation training personnel, and a wide array of regulatory and legal requirements which are not present in the commercial sector.

Critical to bridging these challenges was the close collaboration between the public and private sectors, as well as the extensive direct involvement of end-users in both the military and civilian worlds, which both enabled an agile development paradigm that was laser-focused on actual end-user needs, as well as the generation of support within MAJCOMs required to provide momentum to achieve programmatic status.

Overall, we have demonstrated that VR medical simulation can be a practical, usable tool within the DOD and that current-generation technologies can be leveraged to produce training capabilities that can solve mission needs now, even as new technologies (such as advanced haptics and full-body sensory immersion) are under development.

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