CARE-XR: Saving Lives in Combat Environments with a Virtual Reality Framework

Ana Vianez, Paulo Veloso Gomes, António Marques, Javier Pereira, Gonçalo Pereira, and Yuri Lourenço

LabRP/CIR, ESS, Polytechnic of Porto, Porto, Portugal
CITIC Research Center, University of A Coruña, 15071 A Coruña, Spain
Exército Português, Centro de Tropas de Operações Especiais
Correspondence: acvianez@gmail.com; ajmarques@ess.ipp.pt

DOI: *https://doi.org/10.17979/spu.23.c48*

Abstract: The CARE-XR project (Combat Aid & Response Environment – Extended Reality) presents a practitioner-driven framework for immersive training in Tactical Combat Casualty Care (TC3). Grounded in evidence from a prior systematic review and a Delphi study with Portuguese Special Operations Forces (SOF), CARE-XR combines XR technologies with bio-adaptive affective computing and participatory co-design to address operational needs for realism, adaptability, feedback, and teamwork. The manuscript outlines a phased development process, needs assessment, iterative co-design with SOF, and validation planning, and details the technical components: XR headsets, biofeedback wearables, haptic devices, authoring tools, affective algorithms and simulation management systems. Rather than presenting an efficacy trial, this work is framed as a design and analysis contribution, articulating design requirements, system architecture and ethical considerations. In practical terms, CARE-XR lays the groundwork for a modular and scalable foundation to evaluate transfer of TC3 skills and stress-regulation to live operational contexts.

1 Introduction

The increasing complexity of modern military operations necessitates advanced training solutions that cultivate not only technical proficiency but also robust psychological resilience and decision-making capabilities under extreme pressure. This paper examines the pivotal role of immersive technologies in addressing these critical demands, particularly focusing on the CARE-XR - Combat Aid & Response Environment – Extended Reality. CARE-XR represents a significant advancement, designed to enhance stress regulation and tactical decision-making for Portuguese Special Operations Forces (SOF) personnel in combat medical care scenarios, aligning with Tactical Combat Casualty Care (TC3) principles. Its development integrates cutting-edge bio-adaptive affective computing and a rigorous participatory co-design methodology Dane et al. (2024). Modern military operations present dynamic, unpredictable, and high-consequence environments that impose substantial psychological and physiological demands on personnel Colvin (2014). The capacity to manage acute stress and execute precise decision-making under pressure is critical for mission success and personnel well-being. Despite the recognized importance of stress regulation training, traditional methods face significant limitations regarding scalability, accessibility, and operational realism, which hampers their widespread adoption within defense forces Kirkham et al. (2025).
Immersive technologies, particularly Extended Reality (XR), have emerged as transformative

tools in military training, offering highly engaging, repeatable, and safe environments for practicing cognitive and emotional regulation strategies Baetzner et al. (2025); Gomes et al. (2021)(Baetzner et al., 2025; Gomes et al., 2021). XR platforms enable the simulation of complex combat scenarios that are otherwise challenging to replicate safely in live training, thus allowing service members to develop resilience and tactical competencies in a controlled yet realistic context Baetzner et al. (2025). The decision to initiate the development of the XR environment for Special Operations Forces (SOF) training, with an initial focus on TC3, was directly informed by a rigorous Delphi study, involving SOF specialists, revealed a near-unanimous consensus (97%) that 'combat first aid' represents one of the most critical stressors and urgent training needs for these military personnel.The experts also validated VR as an effective tool for stress management and operational training, emphasizing the importance of features such as realism, scenario adaptability, detailed feedback, and team interaction. These findings underpinned the choice of TC3 as the starting point for the CARE-XR simulation, ensuring the program addresses the most pressing demands validated by the end-users themselves Vianez et al. (2025). Building directly upon these critical insights from the Delphi study and a preceding systematic review, the CARE-XR simulation was meticulously developed as a direct response to the identified operational training needs, particularly within SOF Vianez et al. (2025). This initiative specifically prioritized the training of medical care under fire—rooted in the TC3 framework—as the most urgent domain for immersive scenario-based stress regulation training. This critical area aligns precisely with the principles of TC3, positioning CARE-XR as a highly relevant and specialized training tool designed to meet the unique demands of elite forces Holcomb et al. (2006). The CARE-XR program integrates affective computing principles and a participatory co-design methodology, ensuring an adaptive, user-centered simulation that addresses both technical and emotional demands inherent to combat first aid Dane et al. (2024); Picard (1997). Beyond initial skill acquisition, immersive platforms also demonstrate therapeutic potential, facilitating rehabilitation for conditions such as anxiety and depression, thereby enhancing overall force readiness and resilience Carl et al. (2019); Kluge et al. (2023). This therapeutic application is rooted in the principles of affective computing, a field pioneered by Picard (1997).

The present study details the design, development, and preliminary validation of the CARE-XR immersive simulation. By combining real-time biofeedback adaptation with operationally relevant scenarios co-created with SOF operators, CARE-XR represents a novel approach to enhancing tactical stress management and decision-making in high-stakes medical interventions within combat environments.

2 Tactical Combat Casualty Care (TC3) in Immersive Training

The provision of effective tactical combat first aid in combat environments is a critical and time-sensitive component of military operations, directly impacting casualty survival rates and overall mission effectiveness. TC3 serves as the foundational framework for prehospital trauma care in military settings, guiding frontline responders through evidence-based interventions adapted to the dynamic and high-risk nature of the battlefield Holcomb et al. (2006). As operational environments grow increasingly complex and unpredictable, the integration of TC3 principles into immersive training scenarios—particularly through VR and other XR platforms—offers a powerful means of enhancing both the technical and cognitive preparedness of military personnel Baetzner et al. (2025). By simulating the acute stress, unpredictability, and urgency of real combat situations, immersive TC3 training facilitates the development of rapid, adaptive decision-making and life-saving intervention skills under pressure Baetzner et al. (2025); Holcomb et al. (2006).

2.1 Core Principles of TC3

TC3, often referred to as TCCC represents the comprehensive United States military guidelines for prehospital trauma life support in combat settings. Its primary objective is to reduce preventable deaths on the battlefield while simultaneously ensuring the continuity and success of ongoing military operations. These guidelines are dynamic, undergoing continuous updates by the Committee on Tactical Combat Casualty Care (CoTCCC) to reflect the latest evidence-based practices and battlefield lessons learned Deaton et al. (2024); Joint Trauma System (2025). TC3 is systematically structured into three distinct phases:
1. Care Under Fire/Threat. The overriding priority is tactical: gain fire superiority, protect the force, and move to cover. The typical medical intervention is immediate tour-niquet application for life-threatening extremity hemorrhage when tactically feasible; air-way management is usually deferred to the next phase. Tactical imperatives take prece-dence over clinical ones Savage et al. (2011).
2. Tactical Field Care. Once no longer under effective hostile fire, care follows the MARCH algorithm Bennett and Holcomb (2017); Mabry et al. (2010); Sims et al. (2016):
M — Massive hemorrhage: tourniquets, hemostatic dressings, junctional devices;
A — Airway: from simple maneuvers to cricothyrotomy as indicated;
R — Respiration: treat tension pneumothorax; use chest seals for open chest wounds;
C — Circulation: resuscitation for shock, preferably whole blood if available;
H — Hypothermia: aggressive prevention and active rewarming.
Common adjuncts include managing TBI and eye injuries, providing analgesia and antibiotics, and splinting. CPR is generally not recommended for blast or penetrating trauma without signs of life on the battlefield.
3. Tactical Evacuation Care (TACEVAC). Care during CASEVAC/MEDEVAC largely mirrors Tactical Field Care but allows more advanced procedures (e.g., endotracheal in-tubation by trained and equipped personnel). Continuous monitoring and effective handoff communication are essential Otten et al. (2017).

2.2 XR Applications in TC3 Training

Traditional hands-on medic training often relies on physical simulants like moulage, in contrast, VR and Augmented Reality (AR) are increasingly being adopted for Tactical TC3 training, providing highly immersive experiences that are proving invaluable for skill development and decision-making under pressure Hunt et al. (2021); Schrom-Feiertag et al. (2023). AR tools, for instance, can portray dynamic, high-fidelity visual representations of wounds that evolve over time and adapt to trainee interventions, including use in the trainee's real environment Hunt et al. (2021); Taylor et al. (2018). Notably 84% of Airmen reported an improvement in their medical skills after utilizing VR for TC3 training, illustrating the tangible benefits of this approach (Defense Health Agency, 2025).
Existing platforms are designed to support multiple playable roles, such as Combat Medic or Combat Life Saver, and offer diverse combat environments, ensuring comprehensive training coverage Engineering & Computer Simulations (n.d.); Planchon et al. (2018). Furthermore, formal programs like the Combat Casualty Care Course (C4) by the Defense Medical Readiness Training Institute (DMRTI) integrate simulator technology to provide mission-oriented medical scenarios, guiding students through all phases of TC3, from point-of-injury to Role II scenarios (Defense Medical Readiness Training Institute [DMRTI], n.d.). The demonstrated efficacy and cost-effectiveness of existing VR applications for TC3 training, evidenced by improved medical skills and significant cost reductions, provide concrete validation for the value proposition of immersive technologies in military medical education McGrath et al. (2020). This indicates that further investment in advanced simulations like CARE-XR builds upon a proven track record Hunt et al. (2021). TC3 involves intricate procedures that must be executed

under extreme pressure. Live training for such scenarios is often prohibitively expensive and limited in its ability to provide repeated practice McGrath et al. (2020); Seymour et al. (2002). VR directly addresses this by allowing for ”sets and reps” and ”unlimited opportunities to practice the fundamentals” in a safe, controlled environment Hunt et al. (2021). This repeatability directly facilitates the mastery of complex technical and non-technical skills required in TC3, such as trauma assessment, airway management, and circulation control, leading to enhanced proficiency and muscle memory for critical interventions Hunt et al. (2021).

3 Materials and Methods

The development of the CARE-XR simulation environment employed a combination of Extended Reality (XR) hardware and software, along with bio-adaptive affective computing technologies, to create an immersive and adaptive training environment. Given the scope of CARE-XR, XR is used as an umbrella term encompassing Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), with specific references to VR only when describing fully immersive configurations.
Hardware: XR Headsets: High-definition lightweight headsets supporting VR, AR, and MR modes were used to deliver immersive visual and auditory experiences. The platform was designed to support multiple hardware platforms and varying immersion levels (fully immersive, semi-immersive, or non-immersive).
Physiological Sensors and Wearables: Wearable physiological sensors were integrated to collect real-time biofeedback data essential for bio-adaptive affective computing. These include devices capable of measuring biometric data such as heart rate variability and galvanic skin response to assess stress levels and emotional states.
Haptic Feedback Devices and Peripherals: To enhance realism and immersion, haptic feedback devices and specialized peripherals were utilized. These may include simulated weapons with tactile feedback and hardware that delivers haptic responses to users.
Patient Simulators and Moulage: While XR training reduces reliance on physical simulators, integration with high-fidelity mannequins and standardized patients is possible for hybrid training scenarios, enabling practical medical experiences. Examples include robust, wireless, remotely controlled human patient simulators designed for high-fidelity trauma care training. Software and Platforms: CARE-XR was developed using industry-standard XR development engines such as Unity 3D or Unreal Engine, commonly employed to build complex, interactive virtual environments.
Affective Computing and Biofeedback Modules: Custom software modules were developed to process real-time biofeedback data and implement affective computing algorithms. These enable dynamic simulation adaptation to trainees’ physiological and emotional states, adjusting scenario elements to optimize stress regulation training.
Scenario Authoring Tools: Flexible no-code authoring tools were used to collaboratively create and customize Tactical Combat Casualty Care (TC3) training scenarios with SOF operators. This enabled the design of dynamic, variable simulations with multiple patient avatars and interactions. Simulation Management Systems: Systems such as Medical Training Command and Control (MT-C2) or SIMULATIONiQ CORE were considered for remotely managing training platforms, integrating medical scenarios, controlling mannequins, and enabling audio-video surveillance and recording. (Education Management Solutions, n.d.) (PEO C4I (PMW-150), 2023).
AI-Powered Patient Simulation Platforms: Integration of Natural Language Processing (NLP) and AI into simulated patients, as seen in the nXcomms project, enhances training by enabling more realistic and dynamic interactions. Platforms like VRpatients® and SimX offer customizable dialogue and immersive environments (VRpatients, n.d.) (SimX, n.d.) (BioMojo LLC, n.d.).
Data Logging Mechanisms: A robust data logging mechanism was implemented to record be-

havioral and experimental data with precise timing, including user movement, performance, and simulation events for post-action review and detailed feedback.

3.1 Methods

The development of CARE-XR followed a user-centered, iterative, and evidence-based methodology to ensure the simulation addressed critical training needs of Portuguese Special Operations Forces (SOF). To ensure accessibility for readers outside the military domain, acronyms such as SOF (Special Operations Forces) and TC3 (Tactical Combat Casualty Care) are introduced in full upon first mention.

3.2.1. Study Design

A design and development approach was employed, incorporating a Delphi study for needs assessment and concept validation, followed by a participatory co-design process. This sequential process ensured that the end product was grounded in both operational expertise and empirical evidence. The objective was to design a training tool that enhances stress regulation and tactical decision-making in combat medical scenarios, with future plans for preliminary validation.
Delphi Study and Co-Design: Portuguese SOF experts participated in the initial phases. Selected for their expertise in combat operations, tactical first aid, and military training, these participants formed the expert panel in the Delphi study, aiming to reach consensus on training needs and the effectiveness of XR-based interventions.

3.2.2. Development Process

Phase 1: Needs Assessment and Requirements Definition: A rigorous Delphi study was conducted with SOF experts to identify the most critical stressors and urgent training needs, with particular emphasis on "combat first aid" (TC3). The study validated XR—particularly VR configurations—as an effective tool for stress management and operational training, highlighting the importance of realism, scenario adaptability, detailed feedback, and team interaction. These findings directly informed the selection of TC3 as the initial focus of the CARE-XR simulation.
Phase 2: Co-Design and Iterative Development: Building on Delphi insights and a prior systematic review, the CARE-XR simulation was developed using a participatory co-design methodology. SOF operators actively co-created operationally relevant scenarios, ensuring alignment with real-world combat challenges. Bio-adaptive affective computing principles were integrated into the design, enabling real-time adaptation to trainees' physiological and emotional states, including algorithms to interpret biofeedback and dynamically adjust scenario difficulty or environmental elements (e.g., combat sound intensity, visual distractions, task urgency).

4 Conclusion and Future Work

CARE-XR presents a practitioner-driven framework for TC3 training under opera-tional stress, combining XR, bio-adaptive affective computing, and participatory co-design. Informed by a systematic review and a Delphi process, it justifies the focus on combat first aid and outlines a modular training ecosystem with physiological monitor-ing, real-time adaptation, and performance analytics. As a design-and-development con-tribution (not an efficacy study), it defines operational requirements, demonstrates the technical integration of affective computing into tactical medical training, and offers a replicable path that other teams can adapt. The main limitation is the absence of outcome data. Next, we will run controlled validation studies with objective performance metrics; rigorously train and test affective algorithms against independent ground-truth stress and cognitive-load measures; evaluate transfer and ecological validity in live-field TC3; monitor safety over time (e.g., cybersick-ness, sensitization/habituation); and assess organizational, logistical, and cost–benefit factors for adoption. These steps will clarify CARE-XR's effectiveness, safety, and operational utility and guide iterative refinement.

Bibliography

A. S. Baetzner, Y. Hill, B. Roszipal, S. Gerwann, M. Beutel, T. Birrenbach, and C. Wrzus. Mass casualty incident training in immersive virtual reality: Quasi-experimental evaluation of multimethod performance indicators., 2025.

B. L. Bennett and J. B. Holcomb. Battlefield trauma-induced hypothermia: Transitioning the preferred method of casualty rewarming. *Wilderness & Environmental Medicine*, 2 Suppl(28): S82–S89, 2017.

E. Carl, A. T. Stein, A. Levihn-Coon, J. R. Pogue, B. Rothbaum, P. Emmelkamp, G. Asmundson, P. Carlbring, and M. B. Powers. Virtual reality exposure therapy for anxiety and related disorders: A meta-analysis of randomized controlled trials., 2019.

N. M. Colvin. A complex adaptive systems approach to the future operational environment. [Master's thesis, Army Command and General Staff College, School of Advanced Military Studies]. Defense Technical Information Center., 2014.

G. Dane, S. Evers, P. van den Berg, A. Klippel, T. Verduijn, J. O. Wallgrün, and T. Arentze. Experiencing the future: Evaluating a new framework for the participatory co-design of healthy public spaces using immersive virtual reality, 2024.

T. G. Deaton, B. Drew, H. R. Montgomery, and F. K. Butler Jr. Tactical combat casualty care (tccc) guidelines. *Journal of Special Operations Medicine: A Peer Reviewed Journal for SOF Medical Professionals*, 1(24):100–108, 2024.

Engineering & Computer Simulations. Tc3sim: Tactical combat casualty care simulation. ECS, n.d.

P. V. Gomes, A. Marques, J. Donga, C. Sá, A. Correia, and J. Pereira. Adaptive model for biofeedback data flows management in the design of interactive immersive environments. *Applied Sciences*, 11(11):5067, 2021.

J. B. Holcomb, L. G. Stansbury, H. R. Champion, C. Wade, and R. F. Bellamy. Understanding combat casualty care statistics. *The Journal of Trauma: Injury, Infection, and Critical Care*, 2(60): 397–401, 2006.

E. A. Hunt, J. M. Duval-Arnould, K. L. Nelson-McMillan, J. Vasquez, J. Hill, and E. Lin. Simulation and virtual reality: Current perspectives and future directions in medical education. *Academic Medicine*, 7(96):999–1004, 2021.

Joint Trauma System. Committee on tactical combat casualty care (cotccc), 2025.

R. Kirkham, C. Liu, T. Wulundari, E. Aidman, M. Yucel, J. Wiley, and L. Albertella. Emotion regulation and coping in active military personnel: A systematic review. stress and health. *Psychosomatic Medicine*, 3(40):e70036, 2025.

M. G. Kluge, S. Maltby, C. Kuhne, N. Walker, N. Bennett, E. Aidman, E. Nalivaiko, and F. R. Walker. Evaluation of a virtual reality platform to train stress management skills for a defense workforce: Multisite, mixed methods feasibility study., 2023.

R. L. Mabry, J. W. Edens, L. Pearse, J. F. Kelly, and H. Harke. Fatal airway injuries during operation enduring freedom and operation iraqi freedom. *Prehospital Emergency Care*, 2(14): 272–277, 2010.

J. McGrath, A. McFadyen, and L. Reynolds. The cost-effectiveness of virtual reality training for emergency medical personnel: A systematic review. *Simulation in Healthcare*, 1(15):33–39, 2020.

E. J. Otten, H. R. Montgomery, and F. K. Butler. Extraglottic airways in tactical combat casualty care: Tccc guidelines change. *Journal of Special Operations Medicine: A Peer Reviewed Journal for SOF Medical Professionals*, 4(17):19–28, 2017.

R. W. Picard. *Affective computing*. MIT Press, 1997.

J. Planchon, A. Vacher, J. Comblet, E. Rabatel, F. Darses, A. Mignon, and P. Pasquier. Serious game training improves performance in combat life-saving interventions. *Injury*, 1(49):86–92, 2018.

E. Savage, C. Forestier, N. Withers, H. Tien, and D. Pannell. Tactical combat casualty care in the canadian forces: Lessons learned from the afghan war. *Canadian Journal of Surgery*, 6(54): S118–S123, 2011.

H. Schrom-Feiertag, G. Regal, and M. Murtinger. Med1stmr: Mixed reality to enhance the training of medical first responders for challenging contexts., 2023.

N. E. Seymour, A. G. Gallagher, S. A. Roman, M. K. O'Brien, V. K. Bansal, D. K. Andersen, and R. M. Satava. Virtual reality training improves operating room performance: Results of a randomized, double-blinded study. *Annals of Surgery*, 4(236):458–464, 2002.

K. Sims, H. R. Montgomery, P. Dituro, B. S. Kheirabadi, and F. K. Butler. Management of external hemorrhage in tactical combat casualty care: The adjunctive use of xstat™ compressed hemostatic sponges: Tccc guidelines change 15-03. *Journal of Special Operations Medicine: A Peer Reviewed Journal for SOF Medical Professionals*, 1(16):19–28, 2016.

G. Taylor, A. Deschamps, A. Tanaka, D. Nicholson, G. Bruder, G. Welch, and F. Guido-Sanz. Augmented reality for tactical combat casualty care training. in d. d. schmorrow & c. m. fidopiastis (eds.), augmented cognition. augmented, virtual, and mixed reality: Applications in health, cultural heritage, and industry. *Springer International Publishing*, 1(16):227–239, 2018.

A. Vianez, A. Marques, J. Pereira, and P. V. Gomes. Military stress management training using virtual reality: A systematic review and delphi method., 2025.