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Latent Safety Threats During Simulated Internal Mass Casualty Incidents: A Multicenter Simulation-Based Systems Testing Study

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Original Research

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Abstract

Introduction: Internal mass casualty incidents (MCIs) challenge hospital systems by requiring rapid coordination across clinical, operational, and communication domains. Simulation-based clinical systems testing (SbCST) can identify latent safety threats (LSTs), but cross-institutional patterns in internal MCI preparedness remain poorly characterized.

Methods: We conducted a multicenter simulation-based systems assessment using in situ SbCST and Failure Modes and Effects Analysis (FMEA) during simulated internal MCIs. LSTs were identified through triangulation of structured field observations, facilitator observations, and participant self-report during debriefing. Observations were consolidated through structured review, categorized into system-level domains using the HFMEA (Healthcare Failure Mode and Effect Analysis) framework by multidisciplinary consensus, and prioritized using FMEA with expert scoring followed by consensus reconciliation.

Results: Approximately 75-80 raw observations yielded 53 unique LSTs across 2 hospitals. Recurrent vulnerabilities involved leadership, patient flow, communication, triage, and system interfaces. A substantial proportion were classified as high or very high priority, with comparable median FMEA scores across sites (Site 1: 30 [IQR 24-36]; Site 2: 32 [IQR 24-48]). Mitigation strategies were proposed for approximately 60-65% of LSTs.

Conclusion: Multicenter SbCST identified recurrent, high-priority system-level vulnerabilities across 2 hospitals. Prospective tracking of mitigation implementation and re-simulation are needed to determine whether identified threats are reduced over time.

Introduction

Mass casualty incidents (MCIs), including those occurring within hospital settings, present a significant challenge to health care systems, requiring rapid coordination of clinical care, patient flow, and interdepartmental communication under conditions of extreme stress.[1] The ability of hospitals to implement an effective mass-casualty response plan rapidly and effectively is critical.[2–4] Despite the widespread development of institutional MCI protocols, prior studies have demonstrated variability in hospital preparedness and a persistent discordance between written plans and real-world performance.[5–8]

Simulation has emerged as a high-fidelity method for evaluating hospital preparedness and testing MCI protocols under realistic conditions.[4,9,10] In particular, simulation-based clinical systems testing (SbCST) provides a structured approach for assessing health care systems under operational stress and identifying latent safety threats (LSTs), defined as previously unrecognized system-based conditions that may contribute to patient harm if unaddressed.[11,12] Furthermore, integrating SbCST with structured risk analysis methods such as Failure Modes and Effects Analysis (FMEA) enables prioritization of identified threats and supports targeted mitigation strategies.[13–15]

The use of in situ simulation to identify LSTs has been well described across diverse clinical settings including procedural suites, neonatal resuscitation programs, and newly commissioned facilities.[16–18] However, its systematic application to internal MCI preparedness remains substantially underexplored. Existing disaster simulation studies have largely employed tabletop exercises, external MCI scenarios, or regional full-scale drills, with relatively few employing in situ SbCST to evaluate system performance during simulated internal events.[9,19] Furthermore, whether the system-level vulnerabilities identified through this methodology are consistent across different institutional contexts, an important consideration for developing generalizable preparedness frameworks, remains poorly characterized.

The objective of this study was to use a multicenter SbCST approach to identify and characterize LSTs during simulated internal MCIs at two hospitals, and to prioritize these

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threats using an FMEA-based framework, with the aim of characterizing cross-institutional patterns of system vulnerability in internal MCI preparedness.

Methods

Study Design and Setting

This study describes a multicenter SbCST initiative conducted at 2 hospitals to evaluate preparedness for internal MCIs. Both exercises were performed in situ and simulated a missile strike within an inpatient hospital ward. The simulations were designed to assess system performance under conditions approximating real-life operational stress. Each exercise incorporated multiple operational zones, including inpatient wards, evacuation pathways, casualty collection points, emergency department (ED) intake areas, and designated holding areas.

This study was conducted as a quality improvement initiative. Institutional Review Board (IRB) exemption was obtained for one participating site, and the second site was included as part of operational quality assurance activities. No patient data were used.

Project Team and Preparation

The project was led by SimulTech, the simulation center of Clalit Health Services. An interprofessional, multidisciplinary project team was established, including simulation experts, institutional clinical leadership, emergency preparedness leads, and emergency medical services (EMS) personnel.

A structured needs assessment was conducted at each participating institution, including a detailed review of local internal MCI protocols and operational workflows. Based on this assessment, each simulation scenario was tailored to reflect the specific organizational structure, patient flow pathways, and emergency response processes of the respective hospital.

The simulation team developed site-specific structured observation tools for each exercise. These tools were aligned with institutional emergency protocols and informed by standardized observation templates from the Home Front Command, enabling systematic evaluation of system performance across key domains.

Simulation Scenario and Participants

The simulation scenarios were designed to represent internal MCIs within a hospital ward. Each scenario began at the point of impact and included the full continuum of care following site-specific protocols for patient movement to the ED or evacuation to a tertiary center.

To ensure maximal realism, the exercises utilized a "hands-on" approach where all clinical and logistical actions were performed in real time. Standardized patients (actors) were used to simulate conscious casualties, while high-fidelity manikins were utilized for patients requiring invasive procedural interventions.

The exercises incorporated systematic patient search and evacuation, followed by patient flow through predefined hospital pathways. Depending on institutional protocols and operational models, patients were either evacuated to the ED for further evaluation and treatment or transferred to a designated holding area for staging and subsequent evacuation.

Approximately 35 participants were involved at each site, representing a comprehensive cross-section of the hospital response team, including:

- Attending staff and residents
- Nursing staff
- Security personnel
- Emergency response teams
- Emergency medical services
- Patient transport teams

Identification and Processing of Latent Safety Threats

A multi-source data collection approach was used, triangulating observations from 3 complementary streams:

1. *Structured field observations*—Designated trained observers were embedded across distinct operational zones during each exercise: the ward of origin, evacuation pathways, the casualty collection point, and ED intake. Each observer remained assigned to a single zone for the duration of the scenario. Observers used site-specific structured observation tools, developed a priori and aligned with institutional emergency protocols, to document system behaviors in real time.
2. *Facilitator observations*—Lead simulation facilitators monitored overall system performance across multiple zones and recorded system-level observations independently from the zone-based observers.
3. *Participant self-report*—During structured debriefing, participants were explicitly prompted to identify moments in which the system (rather than individual performance) created difficulty, delay, or risk. Verbal observations were documented in real time by a designated note-taker and reviewed for accuracy by the facilitation team.

Following data collection, all observations from the three streams were compiled and reviewed by the core simulation team. Duplicate observations, defined as descriptions of the same underlying system condition captured by more than one stream, were consolidated into single entries, requiring agreement between at least 2 team members. Disagreements were resolved through group discussion. The resulting list was then abstracted into underlying system-level threats.[13,20,21]

LSTs were assigned to system-level domains using the HFMEA framework by a multidisciplinary review group comprising simulation specialists, clinical leads, and emergency preparedness coordinators. A preliminary domain assignment was proposed by the lead analyst for each LST, then reviewed by the full group. Discrepancies were discussed until consensus was reached in all cases. The process was conducted independently at each site, and assignments were subsequently compared across institutions.

FMEA Scoring and Prioritization

Each LST was evaluated using an FMEA approach to determine its relative priority for mitigation.[13,21,22]

Each LST was assessed across three domains: severity, probability of occurrence, and detectability. Scoring was performed by a panel of five domain experts including clinical simulation specialists, an emergency physician, a senior nurse educator, and an institutional emergency preparedness lead. To reduce anchoring bias, each panelist scored all LSTs independently before group discussion. Following independent scoring, scores were collated and compared. LSTs on which all panelists' scores fell within one point on each subdomain were assigned the panel mean directly. LSTs with greater variation (>1 point discrepancy on any subdomain) were reviewed in a structured consensus meeting, in which each panelist articulated their reasoning before the group reached a final agreed score. This process was conducted separately and independently at each site. Each domain was scored on a scale

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from 1 (low) to 4 (high). Detectability was defined as the likelihood that the failure would not be recognized before causing harm, with a score of 4 indicating the lowest probability of detection.

A composite priority score (range 1-64) was calculated as the product of the 3 domain scores. Based on previously described methods, LSTs were categorized into 4 priority levels: low (1-16), medium (17-31), high (32-47), and very high (48-64).

Potential mitigation strategies were identified during debriefing sessions at both sites. These included both immediate operational changes and system-level interventions, such as modifications to documentation processes, implementation of alternative communication tools, and augmentation of emergency equipment availability.

Responsibility for implementation of mitigation strategies was assigned to hospital leadership and emergency preparedness teams at each institution.

Results

LSTs

Across both SbCST exercises, approximately 75-80 raw observations of LSTs were identified during the simulations and subsequent debriefing sessions. Following consolidation of duplicate observations and grouping into system-level categories, a total of 53 unique LSTs were identified across the 2 institutions. The number of LSTs identified per exercise was comparable between sites.

The identified LSTs spanned multiple domains, including clinical care processes, patient flow, communication, infrastructure, equipment, and organizational systems. The distribution of LSTs across system-level domains by site is presented in Figure 1, demonstrating a similar pattern across institutions.

Importantly, many of these threats were not confined to isolated clinical tasks but occurred at transition points between stages of care and across operational units.

To further characterize system-level vulnerabilities, key LSTs were grouped into major domains, as summarized in Table 1. These domains reflect recurrent patterns observed across both institutions, particularly in leadership, patient flow, communication, and system interfaces. These domains were derived through grouping of LSTs according to the HFMEA framework, allowing for structured system-level analysis.

FMEA Scores

FMEA is commonly paired with SbCST to prioritize identified LSTs based on their potential impact on patient safety.

Application of FMEA scoring demonstrated a broad distribution of LST priority levels across both sites, with a substantial proportion categorized as high or very high priority, as presented in Figure 2.

Across both institutions, the highest-scoring LSTs were primarily associated with system-level processes, particularly patient flow, communication, and interdepartmental coordination. Median FMEA scores were comparable between sites (Site 1: 30 [IQR 24-36]; Site 2: 32 [IQR 24-48]) (Table 2).

Mitigations

Mitigation strategies were identified for the majority of LSTs during structured debriefing sessions at both sites, with approximately 60-65% of LSTs associated with proposed interventions.

These strategies included both immediate operational changes and broader system-level modifications. Examples included implementation of duplicate documentation processes to ensure continuity of patient information, use of alternative communication tools such as megaphones in environments with limited communication infrastructure, and augmentation of emergency equipment availability through coordination with EMS upon arrival.

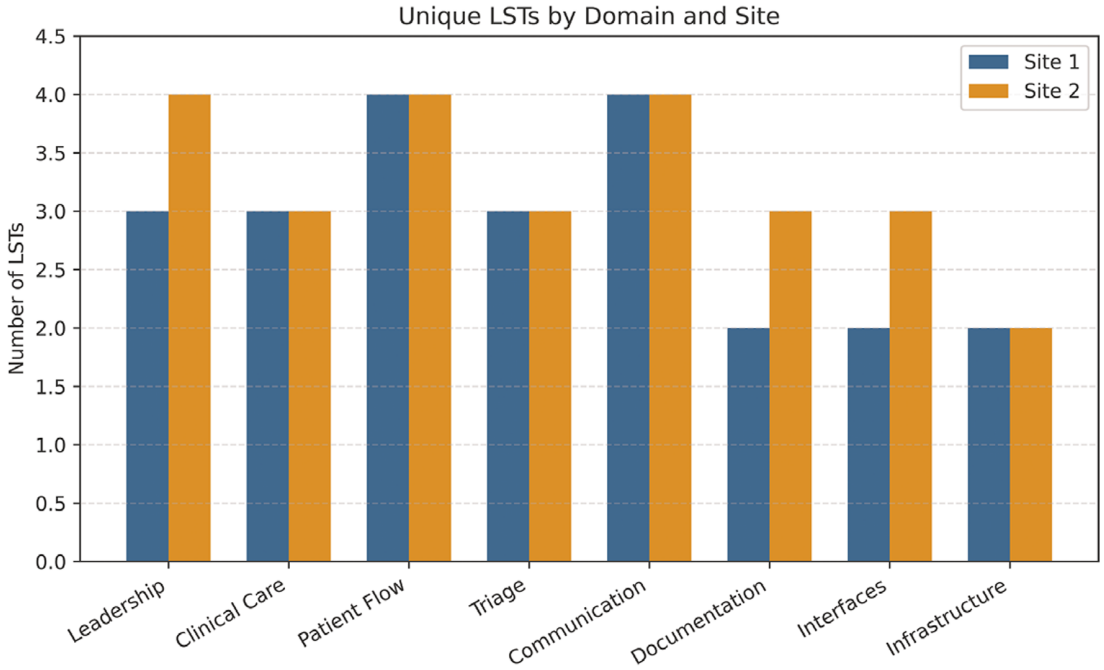


Figure 1. Distribution of latent safety threats (LSTs) by system-level domain across the 2 institutions. A similar pattern of LST distribution was observed across sites, particularly in domains related to patient flow, communication, and clinical processes.

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Table 1. Key system-level latent safety threats identified across both institutions

Domain	Description of threat	Representative example	Potential impact
Leadership and Command	Lack of clearly defined leadership roles and command structure during initial response	Absence of a designated site leader leading to fragmented decision-making	Delayed prioritization, inefficient resource allocation
Clinical Care	Inconsistent execution of essential life-saving interventions and primary survey processes	Failure to perform structured ABCDE assessment and delayed hemorrhage control in critically injured patients	Increased risk of preventable morbidity and mortality
Patient Flow and Evacuation	Inefficient evacuation processes and bottlenecks in patient movement pathways	Delays in evacuation due to congestion and limited access to transport routes	Prolonged time to definitive care and accumulation of critically ill patients
Triage and Prioritization	Variability in triage accuracy and delayed identification of high-acuity patients	Misclassification or delayed recognition of critically injured patients	Suboptimal allocation of resources and delayed treatment
Communication and Coordination	Breakdowns in communication between teams and command structures	Delayed recognition of the event as an internal MCI and inconsistent communication with command center	Reduced situational awareness and delayed system activation
Documentation and Patient Tracking	Lack of standardized documentation and failure to maintain continuity of patient information	Incomplete transfer of patient records between care areas	Loss of critical clinical information and impaired decision-making
System Interfaces	Poor coordination between clinical units and supporting services	Delays in coordination with imaging, operating rooms, and blood bank	Disruption in workflow and delays in definitive treatment
Infrastructure and Equipment	Limitations in physical infrastructure and equipment availability affecting operations	Restricted evacuation routes or limited equipment accessibility at point of care	Reduced operational efficiency and compromised patient safety

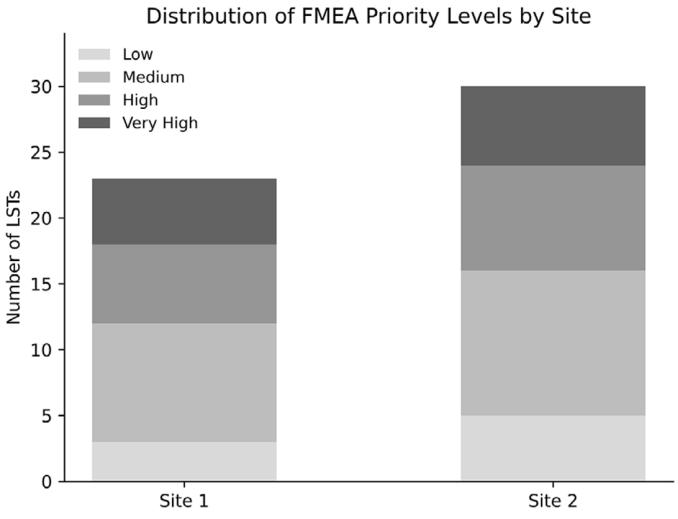


Figure 2. The distribution of FMEA priority levels by site, demonstrating a similar pattern across institutions, with a predominance of medium-to-high priority LSTs.

In addition, several recurring system-level recommendations were identified, including standardization of patient search and evacuation processes, reinforcement of triage and prioritization protocols, clarification of team roles and leadership responsibilities, and strengthening of communication pathways between clinical units and supporting services.

Responsibility for implementation of mitigation strategies was assigned to hospital leadership and emergency preparedness teams at both institutions.

Discussion

This multicenter SbCST study identified numerous LSTs during simulated internal MCIs across 2 institutions. The use of in situ simulation enabled evaluation of real-world system performance under conditions approximating operational stress, providing insight into vulnerabilities that may not be apparent in routine clinical practice.

Key Findings and Significance

The primary finding of this study is the consistency in both the type and severity of LSTs identified across 2 distinct hospital settings. A substantial proportion of LSTs were categorized as high or very high priority, with similar median FMEA scores across sites. The most critical threats were related to patient flow, communication, triage, and coordination across system interfaces. Importantly, many of these vulnerabilities occurred at transition points within the system rather than within isolated clinical tasks. These findings are significant as they highlight that hospital preparedness for

Table 2. Number of LSTs, proposed mitigations, and FMEA scores by site

Site	LSTs identified	LSTs scored	Median LSTs per exercise	Proposed mitigations (% of LSTs)	Median FMEA (IQR)
Meir Medical Center	45–50	23	23	~15 (≈65%)	~30 (24–36)
Magen Ha'ari Hospital	~30	~30	30	~18 (≈60%)	~32 (24–48)
Total	~75–80	~53	26.5	~33 (≈62%)	~31 (24–42)

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internal MCIs depends largely on system-level processes, including coordination, communication, and workflow design, rather than solely on individual clinical performance.

Comparison With Existing Literature

Our findings are consistent with prior studies demonstrating that in situ simulation can effectively identify LSTs before they result in patient harm.[13,14,20,23] In line with previous SbCST studies, including Kerrey et al.,[24] the majority of LSTs identified in our study were related to system processes and interdepartmental coordination rather than individual technical performance. Similarly, studies in simulation-based disaster preparedness have consistently identified communication breakdowns, patient flow challenges, and deficiencies in situational awareness as key contributors to system-level failure.[25–28] Previous work has also demonstrated that integrating SbCST with FMEA provides a structured approach for prioritizing safety threats and guiding mitigation efforts.[22,29,30] In contrast to much of the in situ literature, which focuses on routine clinical environments, the present study extends the SbCST framework to a high-stakes, low-frequency scenario type with distinct operational demands, and demonstrates that the resulting vulnerability profiles are reproducible in character across institutions.

The recurrence of these themes across different institutions and settings supports the generalizability of these findings and reinforces the role of SbCST as an effective tool for uncovering system vulnerabilities.

Strengths

This study has several strengths. The multicenter design enabled comparison across 2 distinct institutional environments, enhancing the generalizability of the findings. The use of a structured methodology combining SbCST with FMEA facilitated both systematic identification and prioritization of LSTs.

A key strength of this work was the use of fully immersive, hands-on in situ simulations rather than tabletop or discussion-based exercises. This approach allowed participants to engage in real-time clinical and operational actions, increasing the realism of the scenarios and more accurately replicating system stress. As a result, it enabled the identification of LSTs that may not have been apparent in more theoretical or method-based simulations.

In addition, the inclusive data collection strategy, incorporating input from facilitators, trained observers, and participants, increased the likelihood of capturing a comprehensive range of system vulnerabilities. Finally, the integration of mitigation strategies into the debriefing process generated actionable mitigation targets for hospital leadership and emergency preparedness teams.

Limitations

This study has several limitations. First, it included only 2 institutions, which may limit generalizability. Second, FMEA scoring was based on expert consensus and is therefore subject to inherent subjectivity. Third, although in situ simulation approximates real-world conditions, it cannot fully replicate the complexity of actual MCI events.

The most significant limitation of this study is the absence of follow-up data on the implementation and impact of the identified mitigation strategies. While mitigation strategies were developed for the majority of LSTs during debriefing and responsibility for implementation was formally assigned to hospital leadership at each institution, the present study did not systematically track which strategies were implemented, at what fidelity, or on what timeline, nor did it assess whether implementation produced measurable improvements in system performance or preparedness readiness.

As demonstrated by Lago et al. in their FMEA-based quality improvement study of pediatric medication safety, re-scoring priority threats after implementing corrective actions combined with structured auditing at defined intervals provides substantially stronger evidence of impact and represents the natural closure of a QI cycle.[31] The present study was designed as a structured initial systems assessment; future work should incorporate this critical follow-up phase, including re-simulation after targeted mitigation and systematic reassessment of priority LSTs at defined time points.

Conclusions

In situ SbCST identified multiple high-priority LSTs during simulated internal MCIs, with consistent vulnerability patterns observed across 2 institutions. The most critical threats involved system-level processes rather than individual clinical performance. The cross-institutional consistency of these findings suggests they may reflect generalizable vulnerabilities in internal MCI preparedness rather than site-specific gaps, and supports the use of SbCST combined with FMEA as a structured approach for identifying and prioritizing system-level risks. Prospective tracking of mitigation implementation and re-simulation following targeted interventions represent the essential next step in translating these findings into measurable improvements in hospital emergency preparedness.

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Author contribution. HKD: Conceptualization, project leadership, study design, data interpretation, manuscript drafting, and critical revision of the manuscript; RS: Data collection, simulation implementation, data review, and revision of the manuscript; ST: Simulation implementation, data collection, data review, and revision of the manuscript; HM: Emergency preparedness expertise, simulation implementation, data collection, and revision of the manuscript; AS: Simulation implementation, data collection, data review, and revision of the manuscript; AP: Institutional oversight, emergency preparedness, and health-system expertise, interpretation of findings, and revision of the manuscript; KB: Simulation coordination, nursing and educational expertise, data collection, data review, and revision of the manuscript.

All authors approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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Ethics approval. This study was conducted as a quality improvement initiative. Institutional Review Board (IRB) exemption was obtained at Meir Medical Center. The second site was included as part of institutional quality assurance activities.

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