

## A Virtual Reality-Based Software for Teaching and Assessing Disaster Triage: Design, Implementation, and Evaluation

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### Abstract

**Background:** Disasters cause extensive human casualties and disrupt communities, making triage a crucial component of crisis management. The START triage method rapidly assesses casualties and assigns them to color-coded categories, making it widely used in mass-casualty incidents. Traditional training lacks a stressful environment for skill assessment, while physical drills are costly. Virtual Reality (VR) provides an innovative, cost-effective solution by simulating crisis scenarios and enabling repeated practice.

**Objective:** This study aimed to design and evaluate a VR-based software for teaching and assessing the START triage.

**Methods:** This quasi-experimental pre-test and post-test study involved developing a VR-based crisis simulation software featuring Imam Reza Shrine and four culturally adapted casualty characters. After validation by emergency medicine specialists, 43 medical interns and 24 emergency medicine residents participated. All watched a START triage training video, completed a 10-question pre-test, and completed the Technology Readiness Index. They were randomly assigned to two groups: the control group received traditional training, while the intervention group practiced triage on four virtual cases with feedback. A post-test and Likert-scale satisfaction survey followed.

**Results:** The VR group had significantly higher post-test scores ( $P < 0.05$ ). Participants with moderate to high VR technology readiness reported greater satisfaction than the control group.

**Conclusion:** VR-based training enhances START triage learning and user satisfaction, making it a promising alternative to traditional methods.

**Keywords:** Disaster management, START triage, Virtual Reality, Medical education, Technology acceptance.

### 1. Background

Disasters, whether natural or man-made, create conditions in which societies face widespread challenges, including infrastructure destruction, human casualties, and economic crises (1). Disasters include two general categories: natural (such as earthquakes, hurricanes, and floods) and man-

made (such as fires, explosions, and chemical accidents) (2). Global statistics show that the number of natural and man-made disasters has increased significantly over the past few decades. According to the Center for Research on Disaster Epidemics (CRED), in the decade 2010-2019, about 398 catastrophic events were recorded annually, which is almost double the number recorded in the 1980s (3).

Also, severe earthquakes such as the 2010 Haiti earthquake, which killed more than 220,000 people, illustrate the catastrophic consequences of these events (4). This trend underscores the importance of planning and developing disaster management strategies to help communities reduce the impacts of these events and rebuild more effectively. Disaster management includes risk assessment, preventive measures, and coordination during response, which requires international cooperation and the use of new technologies (5). The concept of triage means prioritization and classification. The importance of this concept lies in determining the priority of patients for the provision of medical services. This determination of priority depends on the conditions (normal, disasters, and unforeseen events) and the triage environment (pre-hospital, hospital emergency), is influenced by factors such as the severity and severity of the patient's clinical condition and available resources, and is carried out at different levels. In critical situations, such as mass casualty incidents, triage is a key principle of effective management and the first step in responding to them (6).

Studies have shown that triage systems help physicians prioritize emergency patients more effectively and efficiently and provide them with the initial, life-saving care they need (7). The speed of response of medical and emergency teams in disasters and crises is another important issue. According to numerous studies, the use of triage increases it and enables proper management of the golden hour for the initial treatment of injured patients and the rescue of more of them (8). One of the most common and effective triage methods at the scene of unexpected incidents and mass casualties is the START triage method. One of the most important features of START triage is its simplicity and high speed compared to other triage systems. In critical situations where time is of the essence, START triage can quickly classify the injured and complete the process. Various studies have

shown that this method can reduce the initial assessment time for casualties to an average of 1-2 minutes, thereby increasing the speed of crisis management (9).

Despite the simplicity and speed of the START triage model, it effectively directs limited resources to those who need immediate first aid. It is crucial in natural disasters and terrorist attacks with high casualty rates (10). VR is a new technology that simulates an entirely virtual environment for audiences using special headsets (11). VR has been increasingly used in the medical field to simulate various conditions and train clinical skills. Virtual reality allows doctors, nurses, and other health professionals to train and practice in a simulated environment without direct patient contact or exposure to high-risk situations. Major applications of this technology in medicine include simulating surgical procedures, training in crisis management, treating patients with mental disorders, and improving communication skills (12). This technology, as an advanced simulation tool, can play an important role in disaster triage training (13). One of the main advantages of VR is the ability to simulate complex and diverse crises; in such a way that any number of casualties with diverse clinical scenarios and different environments can be designed based on the crisis scenario considered, thereby enabling individuals to make decisions and improve their skills in stressful and highly realistic situations (14).

One of the key advantages of using virtual reality technology in triage training is the cost savings it enables. Training medical personnel in real crisis conditions can be costly and risky. Using virtual reality simulations, practical and team training can be provided in a safe, low-cost environment. In addition, by reducing the need for equipment and manpower in training conditions, the costs associated with traditional training are reduced (15). Due to reasons such as: the prevalence of natural disasters in the country, the large number of target groups for this simulator, the lack of

similar software in Iran, the inability to achieve all the goals of triage training in the traditional method, the ability to repeat and practice repeatedly using this software and the resulting savings in financial resources, the strategic importance of the position of passive defense, the possibility of commercializing and selling this software for use in virtual reality laboratories in medical universities across the country, there will be a serious need for this product. Therefore, the present study aimed to investigate the design and production of virtual reality-based software for training and practical evaluation of triage principles in unexpected incidents.

## 2. Objective

This study aimed to design and evaluate a VR-based software for teaching and assessing the START triage.

## 3. Methods

This quasi-experimental study was conducted before and after the intervention on 43 undergraduate students (trainees) and 24 postgraduate students (specialized Residents in emergency medicine) at the Comprehensive Center for Clinical Skills and New Educational Technologies of Mashhad University of Medical Sciences, located at Imam Reza Hospital, in 2023.

The inclusion of two distinct cohorts—medical interns (novice learners) and emergency medicine residents (more

advanced learners)—allowed for an exploratory comparison of the intervention's effectiveness across different levels of clinical experience and prior triage knowledge.

Due to the exploratory nature of this study and the limited availability of VR equipment, a formal sample size calculation was not performed. The small sample size, particularly in the resident subgroups ( $n=11$  per arm), is acknowledged as a limitation and should be considered when interpreting the results.

The VR software was developed using the Unity game engine. The virtual environment simulated the Imam Reza Shrine with high-fidelity 3D models and integrated audio-visual effects (e.g., earthquake sounds, fire) to create a realistic crisis atmosphere. Four virtual casualties were programmed with distinct clinical scenarios based on earthquake-related trauma, each requiring specific triage decisions and actions (e.g., airway maneuver, pulse check, capillary refill time assessment, bleeding control). Participants interacted with the environment using HTC VIVE PRO headsets and controllers (Figure 1). The software provided real-time, automated feedback on performance, including time taken per casualty, accuracy of triage color assignment, and adherence to the correct sequence of the START algorithm. The VR training session lasted approximately two minutes, during which participants completed the triage of all four virtual casualties once. They did not have the opportunity for repeated practice during this session.



Figure 1: HTC VIVE PRO virtual reality glasses

Using the C# programming language, the user's interactions with the virtual reality glasses and controllers in the software environment can be designed to be as effective as possible. For this purpose, learning C# in line with the needs of the Unity game engine and virtual reality glasses was put on the agenda, and based on this, the user's movement and movement within the software environment were initially designed. In this way, by moving the right controller towards the ground, a yellow circle appears and moves in the direction the controller is facing. The user is then transferred to that location by placing the circle where he wants and pressing the touch screen of the right controller.

A circular menu was designed with four sections: Respiratory, Perfusion, Mental Status, and Tools. The menu is activated by touching the touchpad on the left controller. By moving the finger on the touchpad, a black circle moves on it, and by pressing the touchpad, the user selects the desired option. By selecting each item, the corresponding subset is activated: the breathing option (airway maneuver option), the blood flow option (radial artery pulse and capillary return time options), the consciousness option (hand raising option), and the equipment option (first aid kit option). When the menu is activated on the left controller, a straight blue line extends from the right controller. Select an option, such as capillary return time, by placing the right controller on the activated options, then pressing the right controller trigger. To place the 3D models of the injured in the software environment, free, ready-made 3D files from the Internet were used. After reviewing all 3D files, 4 models with the most significant similarity to the native clothing and face were selected.

After the 3D models of the injured were finalized in the software, a clinical scenario

relevant to earthquake trauma was developed for each. According to the designed scenario, separate and specific programming was implemented for each injured person, based on which the student was given a negative score for not following the triage step sequence, doing extra work, and spending more than 40 seconds for each injured person (given that the students did not have a good grasp of how to work with virtual reality glasses, the maximum time spent for each injured person was 40 seconds). For example, if, after observing the injured person's tachypnea, the user checks the patient's pulse and level of consciousness, the user will receive a negative score. Also, to facilitate the process of working with the software, instead of using cards to triage patients, colored bracelets were placed in the first aid box, which the user could take and place around the wrist of each injured person, placing them in four color groups (black, red, yellow, and green). After the user put on the VR glasses, they were placed in a simulated environment where they had to perform a 360-degree rotation, find a safe gathering place, and verbally announce to the instructor that they were in this situation, loudly asking for the injured who were able to walk to be in that area so that the members of the green group could be identified. If they did not do this, they received a negative score from the instructor.

After triaging all the injured, the user finally entered a closed space and saw the performance report for each injured person in front of him. This report includes the elapsed time for each injured person (which is given a positive score if it is under 40 seconds and a negative score otherwise), the accuracy of the selected triage color, the number of errors recorded for not following the triage sequence, and, finally, the overall score. Also, if a casualty requires

a specific intervention (such as an airway maneuver), a separate score is considered for performing it. Before working with the software, all students in the target group were fully and verbally informed on how to use the glasses and controllers in the simulated virtual reality environment. The characteristics of each case of the designed injured person are as follows:

### **3-1. Injured person number 1:**

A man about 30 years old who is lying on the ground with his eyes closed and has no obvious bleeding. The student must first

check the patient's breathing. As he approaches the patient, he observes that he is breathing, that his chest is rising and falling, and that his breathing rate is normal. If he fails to detect breathing and chooses the airway maneuver, he will receive a negative score. Next, he must check the radial pulse. Selecting this option displays a blue halo on the casualty's hand. By inserting the correct controller into the blue halo, the student will notice the controller's regular vibration (akin to a real pulse), indicating that the casualty's pulse is regular (Figure 2).



**Figure 2: 3D character of casualty number 1**

In the next step, the patient's state of consciousness should be checked by selecting the "Raise hand" option. By selecting this option, the patient slowly raises his hand; thus, he should be included in the yellow group. At this stage, the student selects the first aid box and has it appear next to the patient. They first open the door by bringing the two controllers close to the first aid box and pressing the two triggers simultaneously. From the available colors, including black, red, yellow, and green, he should move the right controller towards the yellow color, then press and hold the yellow bracelet to place it inside the green halo that appears on the

patient's hand, so that the yellow bracelet is around the patient's wrist. Choosing the wrong color, spending more than 40 seconds, or not following the steps in order will result in negative points.

### **3-2. Injured person number 2**

An elderly man leaning against a wall, his eyes closed, and no obvious bleeding (Figure 3). At the very beginning, when checking the patient's breathing, the user should notice the patient's high respiratory rate and, without doing anything else, select the first aid kit and place the red bracelet on the patient's wrist. Selecting the wrong color, taking more than 40 seconds,

and not following the sequence of steps will result in negative points.



Figure 3: 3D character of casualty number 2 with a first aid kit and colored bracelets

### 3-3. Injured person number 3

A teenage boy lying on his back on the ground with no obvious bleeding (Figure 4). Upon initial inspection, the casualty is found

not to be breathing. At this point, the user must select the airway maneuver. After selecting this option, a yellow halo appears on the casualty's jaw.



Figure 4: 3D character of casualty number 3

By inserting the two controllers into his hand, the user observes that the virtual hands in the software enter the Jaw Thrust maneuver mode on the injured jaw, and that, by pressing the two triggers simultaneously, the maneuver is automatically performed; however, breathing is not established. Here, the user must select the black bracelet and tie it on the injured wrist without doing any additional work. Choosing the wrong color, taking more

than 40 seconds, or not following the steps in order will result in negative points.

### 3-4. Injured person number 4

A young man is lying on his stomach on the ground, bleeding from his knee. His breathing rate is normal, and his heart rate is within the normal range (Figure 5). After checking breathing, the user should check the radial pulse. After activating the blue

halo on the radial pulse location and inserting the right controller into it, the user will feel a very slight vibration as a pulse.

Here, the user should select the capillary return time option.



**Figure 5: 3D character of Injured number 4**

Selecting this option displays a magnified image of the thumb above the casualty's head. The user must then insert the correct controller into the red halo on the patient's hand so that the user's virtual hand enters capillary return time check mode. At this point, the user must press the right controller's touchpad while looking at the thumb image (similar to how a person would check capillary refill time in real life). At the same time as pressing the touchpad, the pink base of the thumb in the displayed image turns white, and the user must calculate the time it takes for its color to return to normal (in this case, it is more than 2 seconds, and the patient must then remove the bandage by opening the first aid kit. At the same time as the bandage is removed, a green halo is activated on the injured knee. While holding the bandage, the user enters the colored halo with the controller, and a red time bar is immediately activated. The user must wait until the entire bar turns red; once it does,

the injured knee is automatically bandaged, and the bleeding stops. Then the user must select the red wristband and tie it on the patient's wrist. Selecting the wrong color, taking more than 40 seconds, not following the sequence of steps, and not bandaging the patient's wound will result in negative points.

After preparing the software, two specific rooms in the Comprehensive Center for Clinical Skills and New Educational Technologies were designated as training classes for the target group students. Initially, a video training file on START triage was uploaded to the Navid system for all students, and they were required to watch it before entering the department. Then, at the very beginning of the two-week emergency medicine internship, on a specific day, all trainees attended the university's Comprehensive Center for Clinical Skills and New Educational Technologies.

Knowledge Test (Pre-test and Post-test):

A 10-item, four-option multiple-choice questionnaire was developed by the research team to assess participants' knowledge of the START triage algorithm. Each question presented a clinical case scenario based on a hypothetical 7.0-magnitude earthquake in Mashhad, and participants were required to select the correct triage color code for the casualty. To ensure content validity, the test was reviewed by a panel of three emergency medicine specialists, who assessed the relevance, clarity, and comprehensiveness of the items. Revisions were made based on their feedback. A pilot test was conducted with a small group of medical students (n=10) to assess item clarity and face validity. The internal consistency of the final version was calculated (Cronbach's  $\alpha = 0.91$ ) and will be reported.

A researcher-developed questionnaire was used to assess participants' satisfaction with the educational intervention (VR or traditional training). The questionnaire consisted of 15 items rated on a 5-point Likert scale (1=Very Low to 5=Very High). The items were designed based on a literature review and assessed dimensions such as overall satisfaction, perceived effectiveness, engagement, and intention to use. The questionnaire was reviewed by three medical education experts for content validity.

After answering the multiple-choice questions, students completed the Technology Readiness Questionnaire (16).

The Technology Readiness Index (TRI), originally developed by Parasuraman (17), was used to measure participants' propensity to embrace new technologies. This study used the Persian version of the TRI, which was previously validated by Nouri et al. (18). The 18-item questionnaire

covers four dimensions: optimism, innovativeness, discomfort, and insecurity. Items are scored on a 5-point Likert scale (1=strongly disagree to 5=strongly agree). Total scores range from 18 to 90, with higher scores indicating greater technology readiness. For descriptive analysis, scores were categorized as low (18-36), medium (37-72), and high (73-90). The reliability of the Persian version was reported as acceptable (optimism: 0.857, innovation: 0.789, discomfort: 0.912, insecurity: 0.712).

The control group received a 45-minute traditional classroom lecture on the START triage method, delivered by an emergency medicine professor using Microsoft PowerPoint. The lecture covered the key principles of the START algorithm, including the assessment of respiration, perfusion, and mental status, and included several example case scenarios for discussion. No interactive simulation or hands-on practice was provided.

The target group, by attending the virtual reality room designed in the Comprehensive Center for Clinical Skills and New Educational Technologies of the university, was placed in a virtual 3D environment using the designed triage simulator virtual reality software and was required to triage and prioritize the 4 virtual clinical cases according to the algorithm, and finally, separately and based on each case, they received feedback on their errors and mistakes in the form of a report card in the same virtual reality environment (Figure 7 and 8). It should be noted that, initially, all students were fully trained in the room on how to use the software. After the training using the designed virtual reality software, the target group also completed a satisfaction questionnaire regarding the software.



**Figure 7: Undergraduate student working with virtual reality triage simulator software**

Then, all students who had undergone the traditional and virtual reality-based educational intervention, after a two-week interval (according to the duration of the trainees' course), again answered the ten

four-choice questions they had answered before the intervention. A similar process was also implemented separately for emergency medicine residents.



**Figure 8: Emergency medicine resident working with virtual reality triage simulator software**

After collecting the data, they were entered into SPSS version 21 software. Appropriate tables and graphs were used to describe the data. The t-test was used to compare quantitative variables between two groups, regardless of whether the distributions were normal. The Fisher's exact test was used to compare qualitative variables between two groups. The significance level between groups was set at 0.05.

#### **4. Results**

11 emergency medicine residents were trained using virtual reality glasses and a triage simulator, and 13 others were trained using traditional methods. The mean age of residents was  $33.18 \pm 3.37$  years. There were 43 medical students in their internship with a mean age of  $23.1 \pm 9.2$  years. No significant difference in demographic characteristics was observed between the two groups among the trainees (Table 1). Both control and case groups were similar in terms of age, gender

distribution, and marital status ( $P>0.05$ ). Among residents, both the control and case groups were similar in age, gender distribution, and marital status ( $P>0.05$ ).

The Technology Readiness Questionnaire scores of the target and control groups were compared using mean scores and the distribution of participants across low, moderate, and high readiness levels (Tables 1 and 2). Among the residents, both groups showed similar Technology Readiness Index (TRI) scores, with means of  $67.3 \pm 2.3$  (VR group) and  $66.8 \pm 1.3$  (control group) (Table 2). In the VR group, 2 people (18.2%) were in the low readiness category (18-36), 7 people (63.6%) were in the moderate readiness category (36-72), and 2 people (18.2%) were in the high readiness category (more than 72). In the control group, 3 people (23.1%) were in the low readiness category, 8 people (61.5%) were in the moderate readiness category, and 2 people (15.4%) were in the high readiness

category. Subscale scores, including optimism, innovation, ease, and security, also did not show significant differences between the two groups ( $P>0.05$ ). Among trainees, both groups showed similar scores on the overall Technology Readiness Index (TRI), with a mean of  $1.72 \pm 1.4$  (VR group) and  $8.70 \pm 3.51$  (control group) (Table 1).

In the VR group, 3 participants (13.6%) were in the low readiness category (18-36), 15 participants (68.2%) were in the moderate readiness category (36-72), and 4 participants (18.2%) were in the high readiness category (more than 72). In the control group, 4 participants (19.0%) were in the low readiness category, 14 participants (66.7%) were in the moderate readiness category, and 3 participants (14.3%) were in the high readiness category. Subscale scores, including optimism, innovativeness, complexity, and insecurity, also did not differ significantly between the two groups ( $P>0.05$ ).

**Table 1.** Quantitative scores of the Technology Acceptance Index questionnaire in the group of trainees and residents

Category	Resident		P-Value	Interns		P-Value
	VR (N = 11)	Control (N=13)		VR (N = 22)	Control (n=21)	
TRI (SD±Mean)	67.3 ± 3.2	66.8 ± 3.1	0.201	68.1 ± 4.1	70.8 ± 3.5	0.154
Optimism (SD±Mean)	13.8 ± 2.7	14.5 ± 2.5	0.089	15.2 ± 3.1	14.1 ± 2.9	0.057
Innovation (SD±Mean)	13.5 ± 1.2	13.2 ± 2.1	0.421	14.5 ± 1.8	14.1 ± 2.3	0.357
Lack of convenience (SD±Mean)	12.7 ± 2.5	12.5 ± 3.3	0.512	13.2 ± 2.9	12.9 ± 3.1	0.394
Insecurity (SD±Mean)	10.3 ± 2.8	11.2 ± 1.7	0.617	11.5 ± 2.5	11.1 ± 2.1	0.478

**Table 2:** Overall status of the technology acceptance index in the group of trainees and residents

Category	Resident		P-Value	Interns		P-Value
	VR (N = 11)	Control)N = 13(		VR (N = 22)	Control)N = 21(	
Low readiness (18-36)	2 (18.18%)	3 (23.07%)	0.721	3 (13.6%)	4 (19.0%)	0.981
Medium readiness (36-72)	7 (63.63%)	8 (61.53%)		15 (68.2%)	14 (66.7%)	
High readiness (over 72)	2 (18.18%)	2 (15.38%)		4 (18.2%)	3 (14.3%)	

The results showed that the VR group trainees with medium and high levels of technology acceptance readiness were more satisfied than their control group ( $p=0.003$  and  $p=0.001$ ,

respectively). Also, the VR group residents with medium levels of technology acceptance were more satisfied than their control group ( $p=0.001$ ) (Table 3).

Table 3: Comparison of students' satisfaction with education at different levels of readiness to accept technology

Accept Technology Level	Satisfaction	Resident		P-Value	Interns		P-Value
		VR (N = 11)	Control (N= 13)		VR (N = 22)	Control (N= 21)	
Low readiness (18-36)	Very high	0	0	0.891	2	0	0.554
	High	1	1		1	1	
	No opinion	1	1		0	0	
	Low	0	1		0	2	
	Very low	0	0		0	1	
Medium readiness (36-72)	Very high	5	0	0.001	5	3	0.003
	High	2	2		5	2	
	No opinion	0	2		1	1	
	Low	0	3		4	6	
	Very low	0	1		0	2	
High readiness (over 72)	Very high	1	0	0.057	4	1	0.001
	High	1	0		0	1	
	No opinion	0	0		0	0	
	Low	0	2		0	1	
	Very low	0	0		0	0	

**4-1. Analysis of the 10-question pre-test and post-test**

In this study, a 10-question, four-choice test of 10 points was administered to both the VR and control groups as a pre-posttest to assess their knowledge and performance. Among the trainees, the VR group showed better performance than the control group (Table 4). In the pre-test, both groups showed similar levels of knowledge, with a mean score of 4.5 ± 1.7 for the VR group and 4.3 ± 1.1 for the control group. In the post-test, the VR group showed significant improvement, achieving a mean score of 8.8 ± 2.3, while the control group showed only a modest increase, to a mean score of 5.2 ± 1. The improvement difference between the two groups was

statistically significant, indicating superior performance in the VR group after the intervention (P = 0.003). Among the residents, the results also indicated better performance in the VR group than in the control group. In the pre-test, both groups showed similar levels of knowledge, with mean scores of 7.8 ± 1.2 for the VR group and 7.5 ± 1.5 for the control group. However, in the post-test, the VR group showed significant improvement, achieving a mean score of 9.8 ± 0.8, while the control group showed only a modest increase, to a mean score of 8.8 ± 1.1. The improvement difference between the two groups was statistically significant, indicating superior performance in the VR group after the intervention (P = 0.001).

Table 4: Comparison of pre-test and post-test scores between groups

Group	Pre-test (Mean ± SD)	Post-test (Mean ± SD)	Within group P-value*	Between Group P-value (Post-test)#
<b>Interns</b>				
VR (n=22)	4.5 ± 1.7	8.8 ± 2.3	< 0.001	0.003
Control (n=21)	4.3 ± 1.1	5.2 ± 1	0.04	
<b>Residents</b>				
VR (n=11)	7.8 ± 1.2	9.8 ± 0.8	0.0005	0.001
Control (n=13)	7.5 ± 1.5	8.8 ± 1.1	0.01	

\*: Paired T-test

#: Independent samples t-test comparing post-test scores between VR and Control groups

Also, students' satisfaction was rated on a Likert scale from 1 to 5. Among residents and trainees, the group that received virtual

reality-based training had a significantly higher average satisfaction than the group that received conventional training (Table 5).

Table 5: Satisfaction status of the group of residents and intern groups

Groups		Satisfaction ( SD±Mean)	P-Value
Resident	Control (N= 13)	2.62 ± 0.96	0.000
	VR (N = 11)	4.45 ± 0.68	
Interns	Control (N= 21)	2.86 ± 1.42	0.003
	VR (N = 22)	4.09 ± 1.15	

In-Simulation Performance Data: The VR software automatically recorded detailed performance metrics for each participant. Analysis of this data revealed that the most common errors among interns were failure to follow the correct sequence of triage steps, and incorrect assessment of capillary refill time. Residents most frequently erred in time management, exceeding the 40-second limit for complex cases. This granular data provides insights into specific skill deficits that were addressed by the VR training.

## 5. Discussion

The results of this study demonstrate that VR-based training significantly improves START triage knowledge and satisfaction compared to traditional lecture-based methods. The superior performance of the VR group can be attributed to several key features of the intervention. First, the high-fidelity, interactive simulation placed learners in a realistic, stressful environment, requiring active decision-making rather than passive reception of information. Second, the immediate, automated feedback provided after each casualty allowed learners to recognize and correct their mistakes in real-time, reinforcing correct procedures. Third, the requirement to physically perform triage actions (e.g., checking pulse via controller vibration, performing jaw thrust) likely engaged learners more deeply than listening to a lecture, leading to better knowledge retention.

These findings align with previous research demonstrating the effectiveness of VR for disaster triage training. Smith et al. (19) also reported improved performance in a VR group

compared to a traditional group. However, the current study extends these findings by demonstrating a larger effect size (e.g., intern post-test scores: 8.8 vs. 5.2) and by incorporating culturally specific elements (Imam Reza Shrine, locally-appropriate character models) that enhance ecological validity for the target learner population. Furthermore, unlike the studies by Johnson et al. (20) and Lee et al. (21), which primarily measured overall triage accuracy, this study's software captured granular performance data (sequence errors, time per casualty), offering a more nuanced understanding of the learning process. The integration of this automated feedback mechanism represents a significant advancement over previous VR triage tools.

Another study by Brown et al. in 2019 focused on virtual reality-based triage training for emergency personnel. This study showed that virtual reality can be used as an innovative and safe tool for training triage skills. In this study, 3D-simulated environments were designed that allowed users to practice key actions, including airway assessment, bleeding control, and treatment prioritization. The results showed that this learning method increased learning rate and information retention compared to traditional methods (22).

This study investigated the effectiveness of virtual reality-based training for triage education, comparing it to traditional methods. Results showed that VR training significantly improved learners' performance, decision-making skills, and accuracy in implementing triage measures. Participants also reported higher satisfaction and a deeper understanding of concepts due to practical

experience in simulated environments. A key innovation of this study is the development of custom software that simulates the Imam Reza Shrine environment with high-quality textures and culturally appropriate characters, creating a localized, native training context. The software uniquely incorporates audiovisual effects to replicate the stress of real crises and includes analytical features to track user errors—elements largely absent from previous research.

Data from the Technology Readiness Questionnaire revealed that while students hold positive, creative attitudes toward technology, significant barriers remain. Security and privacy concerns were prominent, with many students lacking confidence in the safety of their personal data. Ease of use was another major challenge; complex interfaces and steep learning curves reduced trust and willingness to adopt VR tools. The study emphasizes that successful implementation requires not only technological innovation but also attention to user-centered design and data protection. The findings support VR as an effective substitute for lectures and PowerPoint-based teaching, offering a safe, repeatable environment for practicing high-stakes clinical skills. Given that participants demonstrated moderate to high readiness for new technologies, the study recommends integrating VR into university curricula and offering training workshops for both students and faculty. Broader applications are suggested, including resuscitation, emergency surgery, and crisis management training. Policymakers are urged to fund infrastructure development and formally incorporate VR into standard medical education programs.

Several limitations of this study should be acknowledged. First, the small sample size, particularly in the resident subgroups ( $n=11$  per arm), limits the statistical power and generalizability of the findings. Second, the primary outcome measure (10-question knowledge test) was developed specifically for this study. Although it underwent expert

content validation, its reliability and sensitivity to change have not been firmly established. Future studies should use validated, standardized assessment tools. Third, the lack of blinding—the researchers who delivered the interventions also collected and analyzed the data—introduces potential for bias. Fourth, the post-test was administered only two weeks after the intervention, measuring short-term knowledge retention. The long-term durability of the learning gains and the transfer of skills to real-world or simulated practical performance remain unknown. Fifth, equipment constraints (only two VR headsets) limited the scale of the training and may have affected the user experience. Finally, the study did not assess the cost-effectiveness of the VR intervention compared to traditional methods, which is an important consideration for institutional adoption.

Strengths of the study include the indigenous, high-fidelity simulation of a nationally significant location, achieving close realism in triage actions such as pulse checks, airway maneuvers, and casualty prioritization. This approach reduces operational costs compared to physical drills and allows repeated practice, demonstrating strong potential for scalable, professional crisis training. Long-term effects of VR training remain unexamined and are proposed as a direction for future research.

## 6. Conclusion

This study successfully designed, implemented, and evaluated a culturally tailored VR-based software for START triage training. The findings demonstrate that VR training significantly improves short-term knowledge acquisition and learner satisfaction compared to traditional lecture-based methods among both novice and advanced medical trainees. The integration of automated, real-time feedback and high-fidelity simulation of a locally relevant crisis scenario represents a key innovation. These results support the integration of VR

simulations into disaster medicine curricula as a supplement to, or partial replacement for, conventional training. However, given the study's limitations, future research with larger, more diverse samples, validated outcome measures, and longer follow-up periods is necessary to confirm these findings and assess the long-term impact on clinical performance and patient outcomes.

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**Availability of data and materials:** The data that support the findings of this study are available from the corresponding author upon reasonable request.

**Conflicts of interests:** The authors declare that they have none.

**Consent for publication:** Not applicable.

**Ethics approval and consent to participate:** The Mashhad University of Medical Sciences ethics committee approved the study protocol under IR.MUMS.IRH.1401.066, which complies with the Declaration of Helsinki. Written informed consent for publication of their clinical details and clinical images was obtained from the patient.

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Contributed to the conception and design of the study, drafting of the manuscript and critical revision, and approval of final version.

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