Chemical Casualty Simulation for Emergency Preparedness Training

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INTRODUCTION

For several years, the medical and public health communities have expressed concern over preparedness for terrorism attacks. In 1999, the Institute of Medicine (IOM) recommended that simulation software be developed to provide interactive training for personnel involved in management of chemical or biological (CB) terrorism incidents. The Government Accounting Office later recommended better training for medical, emergency-response, and public health personnel in responding to mass casualties that result from terrorist incidents (GAO-01-915). Additionally, an analysis of 30 hospitals in FEMA Region III found that more than 70% were not prepared for CB or nuclear incidents (Treat, 2001).

Following September 11, 2001 and the anthrax attacks, national funding was provided through the Centers for Disease Control to improve bioterrorism preparedness, as well as other public health emergency preparedness activities, and through the Health Resources and Services Administration to enhance the capacity of hospitals and associated health care entities to respond to bioterrorism attacks. A recent GAO analysis of seven cities, indicated that hospitals still have an insufficient level of training (GAO 03-373).

Traditional medical training cannot provide adequate experience for disasters, such as chemical agent exposure, because these events occur so rarely. Furthermore, medical training is more effective when clinicians receive combined didactic and practical training, such as case discussion, simulated patients, and hands-on workshops (Catlett et al., 2002). The simulation described in this paper provides low-cost training and practice for first responders. The different combinations of simulation parameters (such as the level of complications) provide a rich set of varying scenarios for the learner to use for practice.

Overview of this Paper

This paper describes the development of a chemical casualty simulation for training emergency medical personnel. We developed trauma casualty and other patient simulation software under a R&D program called Simulation Technologies for Advanced Trauma Care (STATCare)(Kizakevich et al, 2002). In this paper, we describe the modification of STATCare to support chemical casualty response training. While STATCare was enhanced to support training on reactions to various chemical exposures, in this paper we provide details on the cyanide simulation.

Training Goals of the Simulation

The goal of the simulation is for the learner to determine the appropriate "level of effect" for individual casualties. For example, a treatment for a "moderate" response would differ from that of a "severe" casualty. Therefore the simulation includes a set of casualties for each chemical agent to train responders to identify casualty severity and administer the corresponding level of medical intervention.

SIMULATIONS FOR TRAUMA CARE TRAINING

For several years, RTI has been developing trauma casualty and other patient simulation software under the STATCare R&D program. The chemical casualty simulation enhanced STATCare by:

- Extending the physiological models to include models of chemical agent exposure and treatment,
- Providing realistic, animated representation of patient signs and symptoms, and
- Integrating these advancements into casualty scenarios for practice of chemical casualty care.

STATCare Patient Simulator

STATCare provides realistic medical practice across multiple occupational domains and workplace environments. Medical providers can sharpen assessment and decision-making skills, as well as develop an appreciation for patient responses to appropriate or inappropriate treatment.

STATCare guides the user through standardized protocols and then challenges the user with complex scenarios. The Learn mode provides step-by-step, interactive instruction on patient assessment and care. The Practice mode allows scenario-based practice at a self-set pace with free-play of any interaction. An In-Progress Review is provided to check performance against standard protocols. In each learning mode, the patient becomes better, stabilizes, worsens, or dies depending on the care provided. All user interactions are recorded for after-action reviews, as are the pertinent physiological data.

STATCare Simulation Scenarios

The STATCare simulator, as shown in ***Figure 1***, presents a scenario comprising a setting (e.g., trauma scene, medical clinic, emergency room), conditions, and one or more patients. The caregiver can navigate and survey the scene, interact and converse with each virtual patient, use medical devices, administer medications, monitor data, and perform interventions. To interact physically with the virtual patient (e.g., take a pulse), the user right-clicks on the body region of interest (i.e., the wrist). A pop-up menu appears near the selected region, and an interaction may be selected (i.e., Assess pulse). In this case the pulse rate and quality (i.e., weak and thready) would be reported.

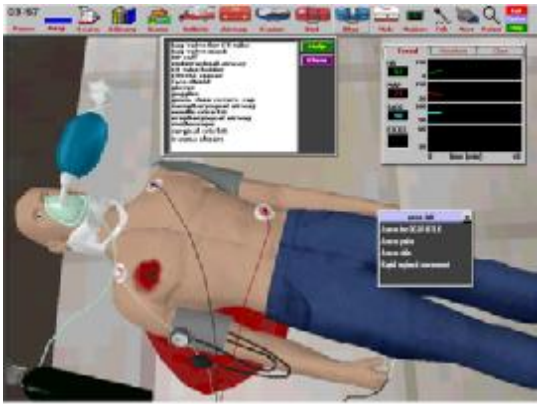

Figure 1. Interactive 3D virtual patient.

STATCare Physiological Simulation

The STATCare physiological simulation integrates real-time cardiovascular, respiratory, and pharmacokinetic models. A supervisory layer provides overall control of the simulation, controls the BODY Simulation™ physiology model, and stores data for subsequent review (Smith 1998).

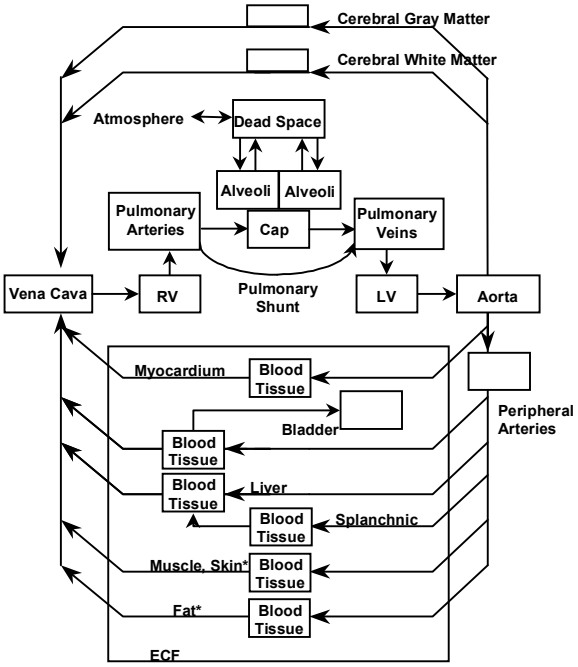

Figure 2. Multiple-compartment transport model.

The multiple-compartment BODY transport architecture represents physiological functions and pharmacological actions and interactions. Just like the human body, the physiology model centers around a cardiovascular model that consists of a beating heart; blood with which to transport gases, ions, chemicals, drugs, etc.; and compartments such as the brain, heart, and liver. The pulsatile cardiac function provides blood pressures and flows that resemble the real cardiovascular system and adds to the realism of the simulation.

CHEMICAL CASUALTY SIMULATION

Chemical agents are typically categorized by physiological action or military use (Jane's, 2000). The principal categories are nerve, blister, choking, blood, and incapacitating agents. Each has a different toxic syndrome and consequently presents with differing signs, symptoms, and casualty behaviors.

Nerve agents (anticholinesterase) (such as Tabun, Sarin, Soman, and VX) inhibit the cholinesterase enzymes. This inhibition creates an accumulation of acetylcholine at cholinergic synapses that disrupts the normal transmission of nerve impulses.

Blister agents (vesicants) include sulfur mustard, nitrogen mustard, arsenicals (lewisite), and phosgene oxime. Blister agents produce pain and injury to the eyes, reddening and blistering of the skin, and when inhaled, damage to the mucous membranes and respiratory tract. Mustard may produce major destruction of the epidermal layer of the skin.

Choking agents include phosgene, diphosgene, chlorine, and chloropicrin. These agents produce injury to the lungs and irritation of the eyes and the respiratory tract. They may also cause intractable pulmonary edema and predispose to secondary pneumonia.

Blood agents include hydrogen cyanide and cyanogen chloride. These agents are transported by the blood to all body tissues where the agent blocks the oxidative processes, preventing tissue cells from utilizing oxygen. The CNS is especially affected and leads to cessation of respiration followed by cardiovascular collapse.

Incapacitating agents produce temporary physical or mental effects, or both. These include Mace®, capsaicin (pepper-spray), and CR (a British agent) with primary effects of burning and stinging of the mucous membranes (eyes, nose, mouth), difficulty with breathing, and irritation of the skin. They also include the anticholinergic agents BZ and Agent 15. The initial effects of these agents are manifested in secretory dryness, hypothermia, cutaneous vasodilatation, pupillary dilation, and tachycardia. Subsequent incapacitating CNS effects include mental status changes, drowsiness, coma, delirium, slurred speech, poor coordination, hallucinations, paranoia, and phantom behaviors.

To adequately represent such casualties, we determined that our virtual patients must be:

- **physiological**, with dynamic models of exposure, health effects, treatment, and recovery
- **animated**, enabling visualization of signs and behaviors like convulsions, vomiting, coughing
- **skinnable**, with variable appearance to visualize cyanosis, rashes, lesions, and skin reddening
- **vocal**, with lifelike conversation and behavior, for reporting of symptoms and events
- **dynamic**, with changing physiology, signs, and symptoms depending on exposure and treatment
- **interactive,** for assessment of medical condition
- **mobile**, moving about the scene in a purposeful or other manner, as with a dazed casualty
- **multiple**, allowing practice of triage in a dynamic mass casualty simulation

Our medical advisors suggested that at most two chemical agents should be developed initially. Nerve agents are always at the top of the list as they are very deadly and were used in the Tokyo Subway attack of 1998. Cyanide is equally deadly, is widely available as an industrial chemical, and is inexpensive. The experts recommended that we start with a cyanide casualty simulation and follow up with nerve agent and other chemicals based on our cyanide experience.

CYANIDE PHYSIOLOGY SIMULATION

Cyanide Pathophysiology

Cyanide generally is considered to be a rare source of poisoning; however, cyanide exposure occurs relatively frequently in patients with smoke inhalation from residential or industrial fires. Cyanide affects virtually all body tissues. Its principal toxicity results from inactivation of cytochrome oxidase (cytochrome aa_3) thereby affecting cellular respiration, even in the presence of adequate oxygen stores. Cyanide binds to cytochrome oxidase, blocking cellular oxygen utilization and forcing an eventual shift to anaerobic metabolism. Consequently, the tissues with the highest oxygen requirements (e.g., brain, heart, liver) are the most profoundly affected by acute cyanide poisoning.

Fatality occurs in seconds to minutes following inhalation, in minutes following ingestion of soluble salts, or minutes (hydrogen cyanide) to several hours (cyanogens) after skin absorption. Rapid therapy, emphasizing supportive care in combination with antidotes, may be lifesaving. Physical findings are generally nonspecific, including the following:

General

- Despite poor perfusion, skin color may remain pink from high arterial and venous oxygen saturation and the reddish pigmentation of cyanmethemoglobin
- Vital signs are variable.
- Initial tachycardia and hypertension may rapidly give way to bradycardia or a relatively normal heart rate accompanied by hypotension.

- Tachypnea and hyperpnea generally precede apnea.

Head, eye, ear, nose, throat

- One potentially useful finding is manifested by bright red retinal veins and arteries, which are caused by absent tissue oxygen extraction.
- The smell of bitter almonds on the breath suggests exposure, yet this cannot be detected by a significant portion of the population.

Cardiovascular

- Cyanosis (bluish skin) is uncommon, even in cardiovascular collapse or arrest.
- Pulmonary findings other than tachypnea are nonspecific.
- Hypertension, hypotension with tachycardia, bradycardia, arrythmia

Respiratory

- Transient hyperpnea; decreased O2 consumption; hyper SvO2; reddish skin; bradypnea, and apnea

Neurological

- Confusion or drunken behavior to coma.
- Headache, anxiety, seizure, convulsions, death

Metabolic

- Elevated blood lactate; metabolic acidosis

Physiological Modeling

Initial simulations of cyanide exposure focused on achieving both the physiological and temporal behavior of the agent and its antidotes. Since the primary mechanism of cyanide toxicity is prevention of oxygen utilization, we modified the model to mimic cellular hypoxia rather than merely reducing oxygen consumption. Figure 3 shows key physiological variables and their reactions to an acute (10 sec) exposure to a lethal (35 mg) dose of cyanide. The rapid increase of heart rate and perturbation of mean arterial pressure are responses to catecholamine release. Anaerobic metabolism increases pCO2, followed by respiratory arrest with decreasing SaO2 and eventual death. If 300 mg of sodium nitrite are infused over 5 min, beginning a minute after cyanide exposure, recovery can be achieved (Figure 4).

Cyanide Treatment Modeling

The chemical processes involved in cyanide treatment are illustrated in Figure 4. Each of the treatment agents and internal chemical substances were modeled as a "drug" within the existing model framework. This allowed simulation of the uptake or formation of each substance, pharmacokinetics (i.e., circulation and distribution), concomitant physiological effects, interactions with other chemical constituents, and elimination by metabolism or excretion.

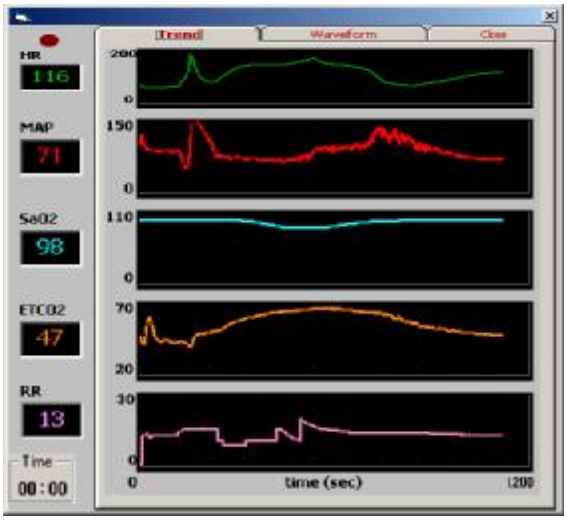

Figure 3. 35 mg cyanide dose resulting in apnea and cardiac arrest.

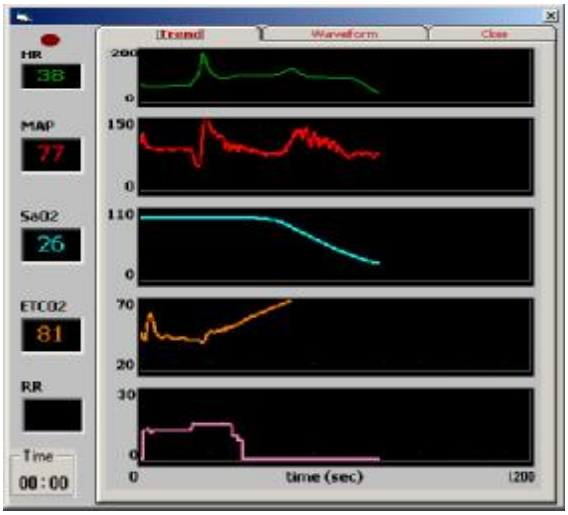

Figure 4. Recovery with treatment beginning 1 minute after cyanide exposure.

The resultant models are quite complex. To ease calculation of mass balance, all chemical processes were computed on a molar basis and assumed to take

place in mixed blood at the vena cava. Nominal values for model properties, such as diffusion coefficients, were set for model development and left for revision later as the simulator becomes more refined.

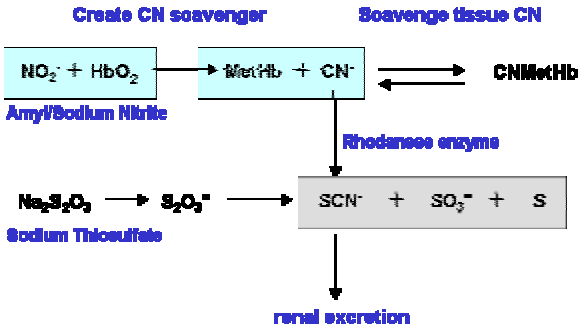

Figure 5. Reactions involved in cyanide treatment.

The first step in treatment is administration of a nitrite. Amyl nitrite or sodium nitrite converts hemoglobin (Hb) to methemoglobin (MetHb). Methemoglobin competes with cytochrome oxidase for cyanide to form cyanmethemoglobin (CNMetHb), and serves as a scavenging agent to pull cyanide from tissue. The CN - MetHb reaction is reversible, so free CN remains in the blood. Since MetHb also reduces the oxygen carrying capacity of the blood, we revised the O_2 transport component of the model to decrease Hb (and O_2Hb) based on the amount taken up as CNMetHb. To rid the body of the cyanide, sodium thiosulfate ($Na_2S_2O_3$) is administered. Thiosulfate converts free cyanide (CN^-) to thiocyanate (SCN^-), which is excreted by the kidneys. All of these reactions occur simultaneously, and are influenced by enzyme activity, process saturation, circulation, and reaction kinetics.

The time course of the integrated cyanide treatment models is shown in Figure 5. Each plot is the blood concentration of a given chemical at the vena cava as a function of time. The scales were adjusted to highlight the dynamic nature and interplay of the various chemical reactions and processes.

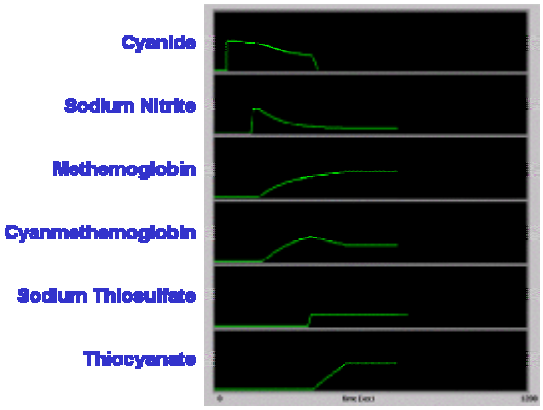

Figure 6 Time course of cyanide treatment models.

After the initial peak, cyanide concentration in the vena cava falls slowly due to circulatory mixing in blood and tissue compartments. With administration of a bolus of sodium nitrite, MetHb begins to form and the concentration of sodium nitrite falls proportionately. As MetHb becomes available, CNMetHb is also formed and cyanide concentration decreases at a rate exceeding that from mixing alone. The concentration of CNMetHb is determined by the combined time courses of available CN and MetHb. With the administration of thiosulfate, free CN in the blood is converted to thiocyanate. Eventually the free cyanide is reduced to zero concentration and the remaining substances are stabilized or excreted.

CYANIDE VIRTUAL PATIENT SIMULATION

Chemical exposure simulations required the following character visualization and behavioral features:

- Dynamic skin texturing of clinical signs & injuries
- Full-body medically-relevant animations
- Multi-layered, deformable & removable clothing
- Breathing integrated with real-time physiology
- Set pupil size and animate pupil response
- Interactive body regions (e.g., wrist, left)
- Attachable medical devices
- Dynamic facial expression (frown, smile, etc.)
- Dynamic speech production (text-based and prerecorded speech with lip shaping)

Virtual Character Modeling

Virtual characters had previously been developed for trauma (Kizakevich et al, 2002), bioterrorism and other diseases (Kizakevich et al, 2003), and mentally-disturbed individuals (Frank et al, 2002). Two additional 3D characters were created for chemical casualty simulation. A 12 year-old boy and a 30 year-

old female were created using 3D character modeling tools and configured with a skeletal system for animation.

Chemical Exposure Symptom Modeling

Chemical exposures require a range of gestures, and because facial expressions are of diagnostic value, they must be as accurate as possible for training or competency testing. To portray these realistic chemical agent casualties, the STATCare graphics subsystem was modified to support animated characters with full-skin texturing.

Chemical Exposure Gesture Modeling

Gestures indicating chemical exposure include convulsions, seizure, muscle twitching, and respiratory arrest. Conscious and semiconscious casualties would also exhibit certain behaviors consistent with a given chemical and level of exposure. For example, profuse salivation, vomiting, or tearing would induce body movements like coughing and wiping the eyes. These are all visual signs that needed to be represented by an animated virtual patient. Such signs and behaviors are of diagnostic value and must be as accurate as possible for training or competency testing.

Animations were initially developed using manual, interactive artistic methods using 3D character development software. This ensured that placeholder characters were available for database and simulation software development. Once the software framework was verified, motion capture data was acquired using instrumented actors playing out the various movements. The motions were captured at a studio called Modern Uprising (Long Island, NY). The animations were then redeveloped using RTI's motion capture data.

Chemical Exposure Facial Expression Modeling

Facial expressions are displayed through the use of 3D morph technology. Like general body motions, facial expressions can depict level of consciousness, reaction to agents, pain, and blink rates. RTI's virtual humans can also display chest motion in response to breathing. The virtual breathing can show normal breathing rates, slow breathing, and labored breathing. To replace the normal skin appearance with injured regions, rashes, and other visual variations, a "texture swapping" technology was developed. Graphic images depicting chemical burns, irritation, and cyanosis in extremities can cover the skin like a decal, thereby altering its appearance to the trainee.

CHEMICAL DISASTER TRAINING AIDS INTEGRATED WITH THE SIMULATION

The medical protocol database has been extended to include links at the step-by-step task and action levels to accommodate related medical training and reference materials. "In process" and "after-action" reviews have been incorporated to provide feedback to the student on the interactions taken, noting which of these interactions are correct or incorrect, and whether the interactions were taken in the correct sequence.

CHEMICAL DISASTER SCENARIOS

A key step in scenario development is to develop realistic scenes for portrayal of chemical exposure events and situations where chemical casualties would likely be encountered. Case-based training requires careful design of the scenarios to meet specific learning objectives and development of virtual patients for those scenarios. A Scenario Studio tool was developed to create patient scenarios for both trauma and medical patient simulations. All scenario and simulated-patient specification data are held in a hybrid object-oriented and relational database

Scenes were created for staging chemical scenarios, including a subway station and an emergency room allowing for pre-hospital and in-hospital simulations. The emergency room scene (Figure 7) is used to train healthcare personnel receiving casualties at a hospital. With this scene, the simulator may be used to train at a higher level of medical care and provide therapies not available to pre-hospital caregiver.

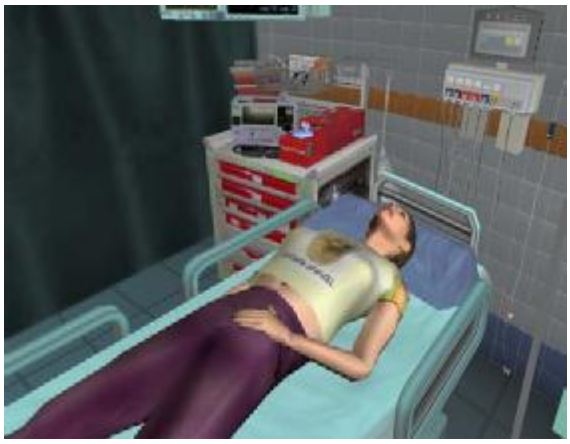

Figure 7. Screen shot of emergency room scenario.

The subway station scene (Figure 4) is used to portray a terrorism event either in a subway car or at the station.
Casualties are presented near the entrance to the station, on a sidewalk in the open environment. In this way, a safe non-exposure environment is available to the caregiver to diagnose and treat the casualty.

Additional scenes were also created for more diversity in civilian and military environments where chemical terrorism might occur or chemical casualties may be treated. These include a city alleyway, a small town street corner, a military "bunker", a high school hallway, a primary care clinic, and a pediatric clinic.

interactive medical care on a desktop computer platform. Using this architecture, simulated casualties were implemented for one hazardous material, cyanide, as a demonstration the prototype system capabilities.

The simulator, with interactive 3D virtual patients, offers considerable advantages over current training technologies. Virtual patients can be readily constructed to represent the range of human diversity, including ethnic, age, race, body habitus, and cultural variations. Virtual patients can be animated, thereby enabling visualization of signs and behaviors like convulsions, vomiting, coughing, tearing, and cramping. Virtual patients can dynamically change their appearance to visualize cyanosis, rashes, lesions,

Figure 8. Screen shot of the subway scenario simulation

CONCLUSIONS

The chemical-agent patient simulator incorporates patient assessment, chemical exposure modeling, physiological modeling, antidote modeling, 3D patient visualization, medically-relevant animation, and

and skin reddening (associated with carbon monoxide and cyanide poisoning). Virtual patients can be interactive, with lifelike conversation and behavior, for reporting of symptoms and events leading to the casualty situation. Virtual patients can be mobile, moving about the scene in a purposeful or other

manner, as with a dazed casualty of a terrorism event. Virtual patients can be multiple, allowing practice of triage in a dynamic mass casualty simulation.

The terrorism events of 2001 emphasize the significance of providing better educational materials for bioterrorism and chemical agent diagnosis and response. We have attempted to meet this need through the research and development of virtual standardized patient for chemical casualty simulation. Our next steps are to validate the quality of the cyanide simulator, add nerve agent and other chemical simulations, and evaluate the training effectiveness of such simulation in a regional medical training testbed.

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