HIGH-FIDELITY TELEMEDICINE SIMULATION IN REMOTE ENVIRONMENTS

TECHNICAL CHALLENGES AND SOLUTIONS FOR HIGH-FIDELITY PATIENT SIMULATION IN SUPPORT OF TELEMEDICINE RESEARCH IN REMOTE AND EXTREME ENVIRONMENTS

By

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ABSTRACT

Telemedicine is emerging as a valuable tool to improve access to health care in pre-hospital and acute care settings. Unfortunately, clinical research and the development of telemedicine technologies are severely limited by the extreme variation in experimental variables alongside legal and ethical concerns.

High-fidelity medical simulation, the use of a robotic manikin that mimics a human patient, may overcome some of these challenges by allowing rare or complex medical procedures to be reproduced in a controlled manner. Improvements in simulation technology have increased the portability of these systems and enabled their use in remote and extreme environments. These locations have limited access to medical resources and expertise, and may benefit greatly from telemedicine support.

This research describes initial attempts at defining the requirements for running high-fidelity simulation in remote and extreme environments in support of telemedicine research. Three additional variations were evaluated to explore possible applications: 1) remote operation and instruction of the simulation, 2) progressive simulations (movement from one location to another), and 3) telemedical support under time delay.

Fourteen 30-minute simulations were conducted on Devon Island, Nunavut, Canada, and on Mauna Kea, Hawaii, USA. Two medically naïve participants rendered care to a simulated patient experiencing an acute medical emergency. Participants were connected through a videoconferencing link over satellite to an experienced physician who provided medical support. All but one simulation was completed successfully, however, all encountered unanticipated technical barriers related to the videoconferencing system, network connection, or simulation technology.

The results show that running high-fidelity patient simulation in extreme environments is technically feasible. They also highlight the importance of rigorous pre-deployment system testing and an appreciation of the effect of network infrastructure and environmental conditions on equipment. Nevertheless, it is clear that high-fidelity simulation holds the potential to unlock new and exciting findings in acute care telemedicine research.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS, CHARTS, DIAGRAMS

LIST OF ABBREVIATIONS

EMS	Emergency Medical Services
A/V	Audio/video
ACLS	Advanced Cardiac Life Support
AED	Automated External Defibrillator
ALSP	Advanced Life Support Pack
ATLS	Advanced Trauma Life Support
BLS	Basic life support
CPR-C	Cardiopulmonary Resuscitation Level ‘C’
CSA	Canadian Space Agency
DRS	Data Redistribution System
DV	Digital video
ECG	Electrocardiogram
ET	Endotracheal
Fps	Frames per second
Gbps	Gigabits per second
HDV	High definition video
HMP	Haughton-Mars Project
HPS	Human Patient Simulator
ISS	International Space Station
ITU	International Telecommunications Union
IV	Intravenous
Kbps	Kilobits per second
LAN	Local area network
LOS	Line of sight
MANOVA	Multivariate analysis of variance
Mbps	Megabits per second

MSE	Mean squared error
NASA	National Aeronautics and Space Agency
NORCAT	Northern Centre for Advanced Technology
OS	Operating system
PIP	Picture-in-picture
PISCES	Pacific International Space Center for Exploration Systems
PTZ	Pan-tilt-zoom
QoS	Quality of service
RAM	Random access memory
RDC	Remote Desktop Connection
SpO_2	Oxygen saturation
SRCan	Space Resources Canada
STARS	Shock Trauma Air Rescue Society
VGA	Video graphics array
VNC	Virtual network computing

1 INTRODUCTION

Telemedicine is emerging as a valuable tool and fundamental component of improving access to health care (Rogers, et al. 2001, Mathews, Elcock and Furyk 2008) and medical education in remote and rural communities (Ricci, et al. 2005). Attempts have been made to evaluate and validate various protocols and technology in pre-hospital and acute care hospital settings, but these have typically been restricted to technology demonstrations and pilot studies (Terkelsen, et al. 2008, Haskins, Ellis and Mayrose 2002, Karlsten and Sjoqvist 2000, Meade and Barnett 2002). Clinical research in this area is severely limited by the extreme variation in experimental variables, such as the rarity or unpredictability of medical emergencies and the training and availability of healthcare providers. Concern is also expressed regarding the legal and ethical issues of using unproven technology in a medical emergency when patient outcomes may be adversely affected.

High-fidelity medical simulation may provide a means to overcome some of the aforementioned challenges. Medical simulation allows for rare or complex medical procedures to be reproduced in a low-risk, controlled environment (Cooper and Taqueti 2004). It involves the use of an electromechanical manikin that can reproduce different physiologic characteristics of a human patient, such as a heart rate with palpable pulses or seizures, and allows for a variety of medical

interventions to be performed, such as peripheral intravenous line placement and defibrillation. There are a wide variety of manikins with different capabilities, but most act as a combination of physical task trainer and physiologic model.

Traditionally, the stage for conducting a medical simulation took place in a simulated operating theatre or hospital room within a dedicated simulation centre (Morgan and Cleave-Hogg 2002), but as the technology improves the portability of these systems is increasing. This portability extends the range of possible environments for medical emergencies beyond the hospital setting, into places such as the rural wilderness and remote communities (Holcomb, et al. 2002, Small, et al. 1999). In parallel, potential beneficiaries may extend beyond hospital-based healthcare providers to include emergency medical services (EMS) personnel, community nurses, and other remote healthcare practitioners. This extension of medical simulation, however, brings with it a set of unique technical and operational challenges and opportunities that need to be addressed to ensure the integrity of an educational program or research initiative.

Running high-fidelity medical simulations in remote and extreme environments as a platform for developing and evaluating telemedicine systems, from a technological perspective, is a novel area of research. The complexity and lack of expertise, however, of running any medical simulation in such hostile locations poses a significant barrier to satisfying any telemedicine research

agenda using this educational technology. The research presented in this thesis describes in detail initial attempts at defining the requirements for running high-fidelity simulation in remote and extreme environments in support of telemedicine research while exploring three additional capabilities and research areas:

1) Enabling distance learning and continuing medical education in remote and rural communities through remote operation and instruction of the simulation.

2) Conducting progressive simulations, which are defined as continuous, end-to-end simulations that start in one location and move to another, for example, from the emergency department to the operating room.

3) Investigating the impact of up to 4 second communication time delays on real-time telemedicine support resulting from satellite connectivity, primitive network conditions, and Earth-Moon distances.

2 LITERATURE REVIEW

Little documented work has been done in the area of high-fidelity clinical simulation outside of a controlled environment. In principle this has largely been limited by the cumbersome peripheral requirements of older simulators on external air compressors, power sources, and wired PC-based control software. It should be noted that much of the experience in running medical simulations in extreme environments might exist in the grey literature, such as proprietary or non-peer reviewed literature. High-fidelity simulation has deep roots in military medical training for medical technologists and front-line physicians who may have used this technology "in the field" and whose documented expertise is not readily available.

2.1.1 Mobile simulation

Previous studies have used medium and high-fidelity simulation to assess the quality of resuscitation using patient simulators in moving ambulances (Havel, et al. 2007) and during a simulated emergency aeromedical evacuation in both a stationary and operational helicopter (Havel, et al. 2007, Wright, et al. 2006). The authors found that simulation improved awareness of the barriers to providing medical care in a helicopter, and found no difference in the quality of CPR between moving helicopters and ambulances.

Additionally, Wyle Laboratories in conjunction with the NASA Johnson Space Center used a high-fidelity simulator in a Falcon DC-9 aircraft to simulate medical procedures conducted in microgravity (Hurst, et al. 2007). They found that management of tension pneumothorax and negative pressure pulmonary edema by an astronaut crew medical officer was sufficient when coached by a flight surgeon on-board the aircraft.

The minimum technical requirements for running medical simulations in extreme environments may be best represented by the Mobile Human Patient Simulator Program of the Shock Trauma Air Rescue Society (STARS) in Alberta, Canada. This group has integrated an entire simulated emergency department room and control room into a motor home, "traveling to rural communities to provide critical care skills training"(STARS 2004). Space, weight, and equipment limitations in such a mobile platform may closely emulate conditions found in remote and rural communities.

The best culmination of multiple experiences in mobile simulation from an operational point of view exists in the textbook *Clinical Simulation: Operations, Engineering, and Management*, which contains three distinct case studies related to the logistical aspects of mobile medical simulation (Kyle and Murray 2008). Unfortunately, the technical details of their setups are not specifically described,

however, significant time is spent on the logistics of organizing and arranging such an event.

2.1.2 Remote operation and distance education

In the United States, a non-profit company named MedSMART Inc boasts to provide "global accessibility and unprecedented affordability by using Human Patient Simulators (HPS) either in hands-on or distance training environments" (MedSMART 2009). However, their approach to distributed learning is highly reliant on a proprietary network and software infrastructure supervised and routed through their headquarters in Ann Arbor, USA along with the consultation of a number of technical personnel to monitor and maintain this network (von Lubitz, et al. 2002).

Another group based at the John A. Burns School of Medicine, University of Hawaii, remotely controlled a simulator at a campus 8 km away and used commercially available videoconferencing equipment at 400 kbps for nursing education of vital signs assessment (Berg, Wong and Vincent 2007).This also appears to have been replicated by a partnership between The Peter M. Winter Institute for Simulation Education and Research and Saint Francis University's Center of Excellence for Remote and Medically Under-Served Areas (CERMUSA 2008).

2.1.3 High-fidelity simulation for telemedicine research

Early work at McMaster University first investigated the use of high-fidelity simulation as a platform for research into the delivery of medical care over a telecommunications link (Musson 2007). These simulations involved a primary healthcare provider (i.e. a nurse or general practitioner) providing care to a simulated patient experiencing an acute medical emergency. Physically separated from them in another room was an advanced cardiac life support (ACLS) certified specialist watching and hearing the simulation unfold, while providing audio-only medical support through a closed loudspeaker system.

2.1 GAPS AND UNANSWERED QUESTIONS

A large motivation for this research stems from the absence of clearly recorded, easily accessible, and summarized experiences in the preparation or operation of these "out-of-hospital" simulations. Several of the papers cited above vaguely outline some of the challenges faced, such as "software malfunction" (Wright, et al. 2006), or indicate their reliance on the technical expertise of local information technology specialists (CERMUSA 2008). Therefore, it is extremely difficult to build on previous experience and lessons learned for newcomers implementing high-fidelity simulation outside of a controlled context.

It is also important to note only one conference paper could be found regarding the integration of high-fidelity simulation with telemedicine research in either controlled or uncontrolled environments (Musson 2007). Given the potential for high-fidelity simulation to address some of the barriers to telemedicine research, outlining initial successes and failures in the integration of the two technologies would be beneficial to the development of future studies.

Running medical simulations in remote and extreme environments and in conjunction with telemedicine research would subject the equipment and simulation operators to a widespread and diverse array of operational challenges, of which only small subsets would be applicable to various contexts. Detailed coverage of these challenges and attempted solutions could benefit those who wish to pursue non-traditional models of providing medical education using simulation or those wishing to use it as a tool to enable research in previously unexplored areas of medical systems analysis.

3 METHODS

The deployment of medical simulation in support of telemedicine research in remote environments was conducted was conducted in three phases. First, preliminary work was conducted at McMaster University to explore the capability of running high-fidelity medical simulation in a field setting. These findings informed the preparation and development of an initial plan and solutions for conducting field research in Canada's High Arctic on Devon Island, Nunavut. Following this deployment, lessons learned were applied to a second field deployment by a volcanic crater on Mauna Kea, Hawaii. All data was collected through direct and participant observation in the planning, preparation, execution, and debriefing stages of the three research phases, and through photo and video records of all field activities.

3.1 PRELIMINARY WORK

Prior to engaging in any research activities in the field, a small pilot project was conducted across the campus of McMaster University using an existing, isolated, wireless network infrastructure for conducting medical simulations remotely. It must be noted that this feasibility study was not conducted over an actual satellite connection as would be present in a truly remote environment, however, its aim was to explore the capability of remotely operating the simulation and audio/video equipment, evaluate bandwidth use, and provide experience running high-fidelity simulation in an atypical environment.

3.1.1 Methods

Four (n = 4) 20-minute medical simulations took place in a high-traffic gymnasium hallway. The simulations were run over a 2.5 hour time period, and were facilitated by 2 simulation evaluators at the remote site. During this time the simulator was controlled remotely using a Windows-integrated Remote Desktop Connection (RDC) and monitored by one novice simulator operator, and two observers at a distance of approximately 600 meters. Two patients were in the simulation: 1) a 20 year old male with broken ribs, represented by a high-fidelity simulator; and 2) his mother, represented by a young adult female standardized patient actor. Each simulation had three medically trained participants providing care.

3.1.2 Results

In general, all simulations were completed uninterrupted, without any major issues on either end of the network. The network remained stable over the 2.5 hour time period from initial network connection to the end of the simulations. Response time by the simulator to changes initiated by the remote operator occurred without any perceivable delay. Informal feedback from the medical teams indicated that all were in favor of high-fidelity simulation training, and that remote operation of the simulator did not negatively impact the simulation or training environment.

Participants commented on the ease and speed of setting up the network connection, less than 15 min by non-expert, non-technical personnel. The simulations occurred during peak network usage in the early afternoon during the academic year. For comparison, data obtained from the McMaster University Network Monitor in the same time period during the quiet summer months indicate a maximum bandwidth use of approximately 100 Mbps of a total 976.56 Mbps. Although bandwidth measurements support data transmission, limitations imposed by satellite infrastructure must be considered. For example, care must be given to address the high bit error rate that can be generated by atmospheric interference, and signal shadowing from large adjacent objects such as steep rises in geographic topography and buildings (Hu and Li 2001).

A few challenges, however, were associated with the remote operation of the simulator. The weight and bulk of the equipment presented some difficulty during transport of the equipment, for instance, the stretcher was too wide to fit through some doors, and a much longer route had to be taken to reach the simulation environment than anticipated. Furthermore, the limited webcam field-of-view angle only allowed one subject to be in focus at a time, usually the simulator. Difficulty observing some interventions performed by the medical team was also reported, especially those requiring fine mechanical manipulation of equipment, such as medication selection and administration. Finally, audio transmissions from the remote site to the operator were virtually unusable given

the intensity of the ambient noise overpowering communication at the simulation site, and intermittent loud static of unknown origin. Fortunately, the medical teams were able to hear the remote operator at all times, for simulation debriefing.

The major issues encountered surround the quality and reliability of the videoconferencing. The poor audio quality and impact of ambient noise highlighted the inadequacy of a built-in webcam microphone, and could have been mitigated by using a separate higher quality directional shotgun microphone with a much higher forward sound sensitivity, improved noise cancelling algorithms, or the use of wireless microphones on simulation participants.

3.1.3 Discussion of preliminary work

This early work demonstrated the feasibility of controlling a high-fidelity simulator and running an emergency medical simulation remotely. Furthermore, it supports the integrity of these activities over a bandwidth limited satellite-based Internet infrastructure, and presents a framework for such an infrastructure. These early lessons impacted the design and preparation for performing and remotely operating medical simulations in an extreme environment, and served as an early test-bed for the technical solutions that were developed and used in this study.

3.2 FIELD SITES

3.2.1 Field deployment 1 – Devon Island, Nunavut, Canada

The first field simulation site was located at the Haughton-Mars Project Research Station (HMP) on Devon Island, Nunavut, Canada (Figure 1). The Mars Institute, a non-profit company whose logistic support is primarily funded by the National Aeronautics and Space Administration (NASA) and the Canadian Space Agency (CSA), manages the camp.

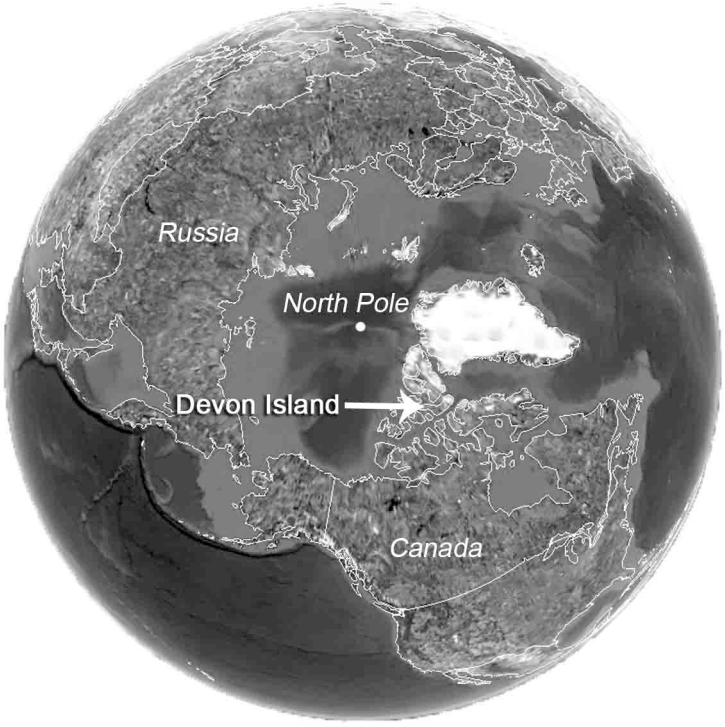


Figure 1 – Location of Devon Island, Nunavut in relation to major geographical landmarks. (Google Inc. 2010, adapted)

The camp acts as a "Mars base analog" and hosts research activities from June to August of each year that include the fields of geology, plant biology, and robotics. The camp population is comprised of a core staff of Mars Institute and Simon Frasier University personnel responsible for setup, maintenance, and tear down of the camp infrastructure. Visiting researchers are graduate students, faculty, and staff from both academia and industry such as NASA Ames, the University of Toronto Institute for Aerospace Studies, and Hamilton Sundstrand.

The camp is situated just outside the Haughton Impact Crater, located at 75°22'N, 89°41'W, approximately 725 km north of the Arctic Circle (Figure 2). The main camp is made up of a set of permanent tents with a collection of temporary individual tents for researchers 200 m from the main camp. Medical simulations took place in the same tent assigned for medical care (Figure 3). The only means for transportation to and from the camp is by a 45-minute flight on a Twin Otter aircraft.

The hostility and remoteness of the field site is reflected by its extreme climate. During the summer months, this arctic desert is characterized by 24-hour sunlight, and temperature variations between -10°C and 10°C with minimal precipitation, in addition to occasional periods of up to 80 km/h winds that prevented air transport for several days at a time, creating a situation where resupply or aeromedical evacuation were not possible.

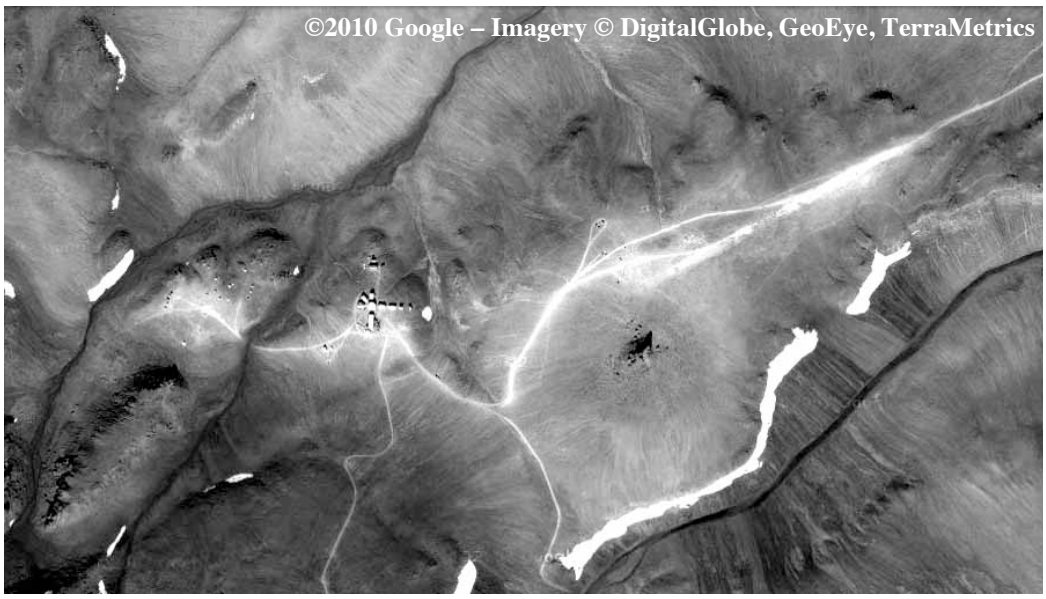


Figure 2 – Satellite image of the Haughton-Mars Project Research Station on Devon Island, Nunavut, Canada. (Google Inc. 2010)

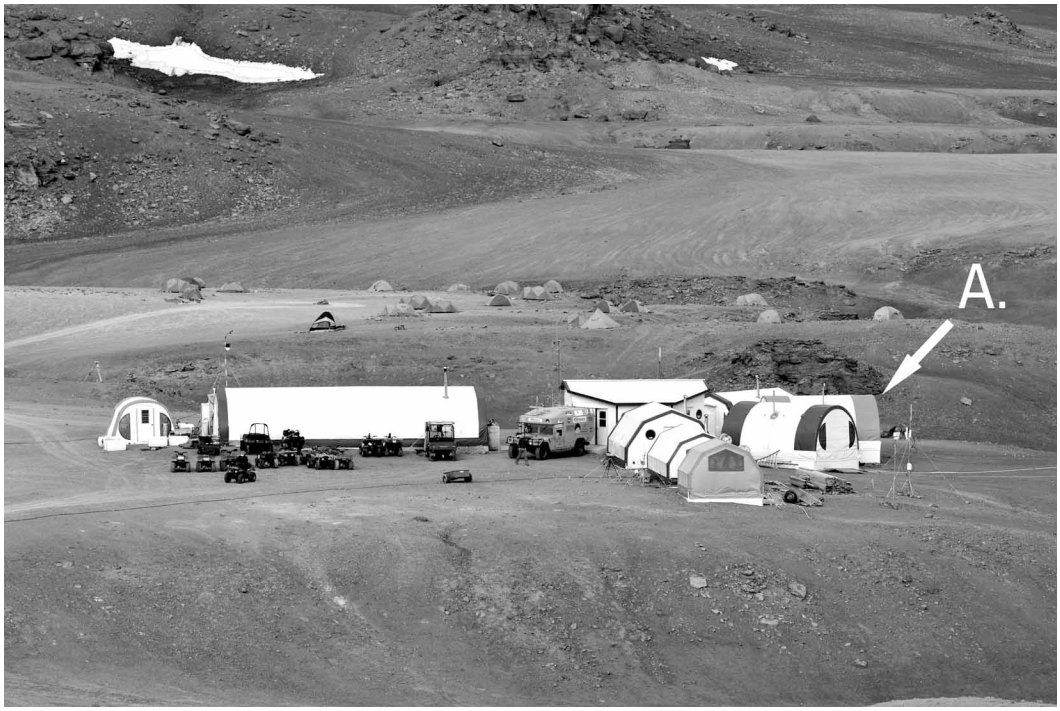


Figure 3 – Haughton-Mars Project Research Station. A) Medical and simulation tent. (CSBL 2009)

3.2.2 Field deployment 2 – Mauna Kea, Hawai'i, USA

The second field simulation site was located at a temporary research camp on Mauna Kea, Big Island, Hawai'i. The collaborative effort was hosted by the Pacific International Space Center for Exploration Systems (PISCES), while the camp itself was managed and operated by the Northern Centre for Advanced Technology Inc. (NORCAT). Both NASA and the CSA funded research activities and infrastructure at the camp. Communications, network infrastructure, and IT support was managed by members of Space Resources Canada (SRCan), a collection of Canadian-based organizations who also developed key technologies tested.

Research activities at the camp were predominantly robotic in nature with investigation into rover technology and in-situ resource utilization in support of space missions to other celestial bodies. The camp was comprised of a core staff of PISCES and SRCan personnel, supporting varied teams of researchers from both academia and industry.

The camp is situated at 2,750 m above sea level on Hawaii's highest inactive volcano Mauna Kea, at 19°45'N, 155°28'W (Figure 4). The main camp was made up entirely of temporary prospector tents, with a dedicated tent for conducting medical simulations located adjacent to the medical care tent (Figure 5). The site itself was located a one-hour drive from the closest hospital, and only accessible by a 4x4 vehicle.

Figure 4 - Satellite image of the research base site on Mauna Kea, Hawai'i, USA. Camp was set up in the highlighted area (actual camp not pictured). (Google Inc. 2010, adaptation)

Figure 5 – Mauna Kea research base. A) Simulation tent behind medical tent. (CSBL 2010)

The 2010 field season duration was from January to February, during the winter months. As the field site lies above the cloud line, precipitation was rare, resulting in a dry, arid, and dusty environment. Extreme temperature variations were present, ranging from -5^{o}C at night to 30^{o}C during the daytime.

3.3 MEDICAL SIMULATIONS

Fourteen (n = 14) 30-minute medical simulation were conducted on Devon Island (n = 8) and on Mauna Kea (n = 6). Each medical scenario involved the care of a simulated patient experiencing an acute medical emergency by 2 medically naïve participants (Figure 6). The participants were guided through a telemedicine link by a remote teleprovider who was an experienced physician located in: 1) Hamilton, Ontario, Canada, 2) New York, NY, USA, or 3) Chicago, IL, USA. Following the simulation was a semi-structured interview with all participants, or "debrief", conducted by a member of the research team, of up to 30-minutes.

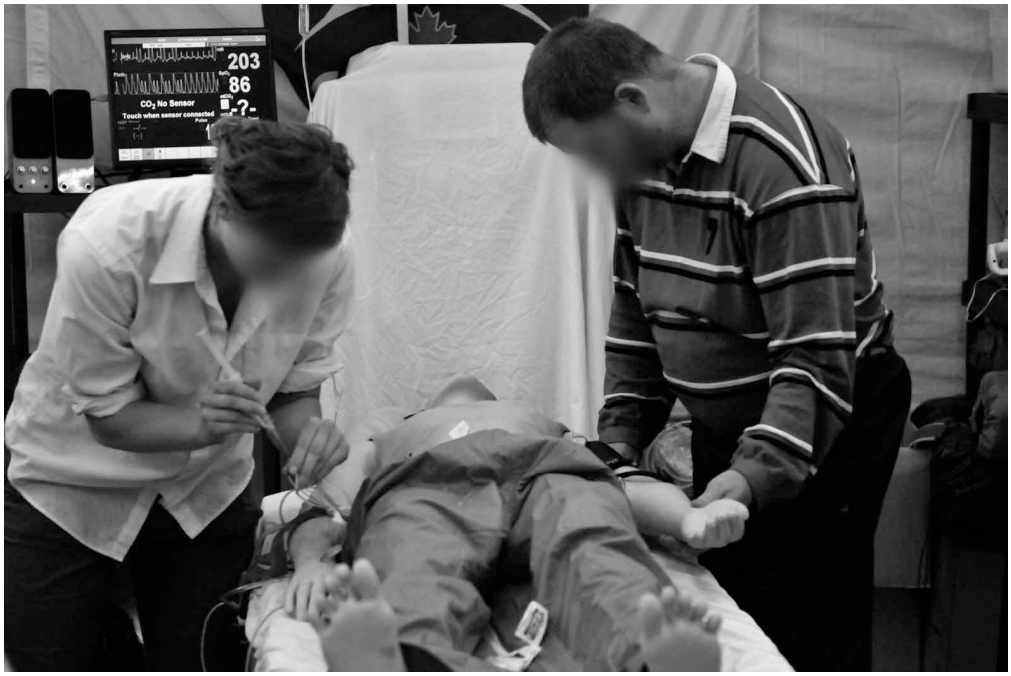


Figure 6 – Medically naïve participants providing care during a simulated medical emergency. (CSBL 2009)

Selected medical conditions were chosen not to be overly complex and were to fall within the scope of ACLS or Advanced Trauma Life Support (ATLS) protocols. They included severe trauma, cardiac arrhythmia and arrest, and airway emergencies. A full breakdown of the simulations is provided in Table 1.

Variations on the operation of simulation were tested to explore various technical conditions. These are listed in **Table 1** under the headings *A/V* and *Notes*, and were not necessarily independent of each other:

- Eleven (n = 11) simulations used Skype (Skype Technologies S.A., Luxembourg, Luxembourg), a commercially available teleconferencing

software, for telemedical support. Three (n = 3) simulations used the Canadian Space Agency's (CSA) Data Redistribution System (DRS), an IP-based video-streaming server platform.

- Three (n = 3) of the simulations were tele-education events involving the remote instruction of on-site participants in basic life support (BLS) and some advanced medical interventions such as intravenous line placement and endotracheal (ET) intubation.
- Three (n = 3) of the simulations included a 4 second time delay.
- One (n = 1) simulation was remotely operated.
- Two (n = 2) simulations were progressive medical extractions beginning at a range of approximately 25 meters from the simulation operator and simulation tent.

Table 1 – Simulations conducted on Devon Island and Mauna Kea.

Date	Simulation	Teleprovider Specialty	Participant Backgrounds		A/V	Notes
Devon Island, Nunavut, Canada						
Jul 17/09	Tele-instruction	Anesthesia	Engineer	Anthropologist	Skype	
Jul 18/09	Multiple traumatic amputations	Anesthesia	Musician	Technician	Skype	
Jul 19/09	AMI[1] to cardiac arrest	Anesthesia and critical care	Engineer	Student	Skype	
Jul 20/09	AMI[1] to cardiac arrest	Anesthesia	Anthropologist	Confederate[2]	Skype	4s delay
Jul 21/09	Head trauma	Neurosurgery	Engineer	Plant biologist	Skype	
Jul 21/09	Anaphylaxis	Cardiology	PA[3]	Engineer	Skype	
Jul 21/09	Atrial fibrillation to cardiac arrest	Cardiology	Plant biologist	Plant biologist	Skype	4s delay
Jul 30/09	Anaphylaxis	Anesthesia and pre-hospital care	Musician	Engineer	Skype	Remotely operated
Mauna Kea, Hawai'i, USA						
Jan 30/10	Tele-instruction	Anesthesia and pre-hospital care	Engineer	Engineer	Skype	
Feb 3/10	Pneumothorax and impaled object	Trauma surgery	Engineer	Engineer	Skype	
Feb 5/10	Head trauma	Anesthesia	Engineer	Biologist	DRS[4]	4s delay
Feb 5/10	AMI[1]	Anesthesia and pre-hospital care	PR[5]	Student	DRS[4]	Extraction
Feb 6/10	AMI[1]	Anesthesia and pre-hospital care	PR[5]	Student	DRS[4]	Extraction
Feb 7/10	Smoke inhalation	Anesthesia and critical care	Engineer	Plant biologist	Skype (audio only)	

[1]Acute myocardial infarction
[2]A member of the investigation team acting as a medically naïve participant
[3]Physician Assistant
[4]Canadian Space Agency's data redistribution system
[5]Public relations

3.4 PARTICIPANTS

A total of 17 participants were recruited between the two field deployments, 11 on Devon Island, and 6 on Mauna Kea. All selected participants were healthy individuals who were either conducting research at the base or a member of the maintenance or management crew. Participants' level of education was widely varied and included everyone from high school students to university professors, each with diverse academic backgrounds including engineering, computer science, biology and music (see Table 1).

With the exception of one participant, the highest level of medical certification held was Standard First Aid with Cardiopulmonary Resuscitation-C (CPR-C). One participant had previous training as a Canadian Forces Physician Assistant Level 6B (independent care). To complete one of the simulations, a member of the research team acted as an additional (18^{th}) medically naïve participant, or "confederate". Participants were excluded if they held a Doctor of Medicine degree or equivalent.

Prior to their first simulation, all participants were given a maximum 3 hour orientation to the simulator and medical equipment in addition to supplementary skills training in basic life support and advanced medical procedures including:

1. Oropharyngeal and nasopharyngeal airways

2. ET intubation
3. Artificial respirations using a bag-valve-mask
4. Auscultation of heart, breath, and bowel sounds using a stethoscope
5. Oxygen delivery via non-rebreather mask
6. Vital signs assessment (blood pressure, pulse rate and rhythm, pupil reactivity)
7. CPR and use of an Automated External Defibrillator (AED)
8. Intravenous (IV) line placement and fluid administrations
9. Management of major bleeds
10. Electrocardiogram (ECG) electrode placement
11. Pulse oximetry
12. Drug administration

Informed consent was obtained from all participants prior to their enrolment. The Hamilton Health Sciences/McMaster University Faculty of Health Sciences Research Ethics Board approved this study.

3.5 DATA COLLECTION

As both field deployments were extremely complex and attempted to satisfy multiple objectives, a diverse array of primary data collected during these expeditions was assembled for analysis. These include the following sources:

1. Audio/video recordings of simulations including debriefing.
2. Photos of the field site, medical tent interior, and medical simulations.
3. Personal notes and records generated through:
    - *Participant observation* in the preparation, execution, and post-deployment phases in support of the simulations.
    - *Direct observation* and open-ended interviews with study participants, interactions with base-camp technical staff, equipment vendors, and co-investigators.

Furthermore, participants' impressions of frame rate, audio/video quality, and simulation realism were extracted from debriefings. A qualitative assessment of the impact of network latency (time delay) and bandwidth on audio/video quality was also conducted in addition to latency and bandwidth measurements collected during several of the simulations.

3.6 SIMULATION ENVIRONMENT

3.6.1 Physical layout

Despite the geographic distance and climatic differences separating Devon Island and Mauna Kea, both simulations were run in a functionally similar environment. Simulations took place in a large, well-lit tent with the simulator lying on a stretcher in its center. On either side of the simulator were spaces for the audio/video equipment and medical equipment and supplies. The simulator

was controlled and observed on Devon Island in the same tent from an area at the foot of the bed, but from an adjacent, physically separated tent on Mauna Kea (Figure 7-Figure 10).

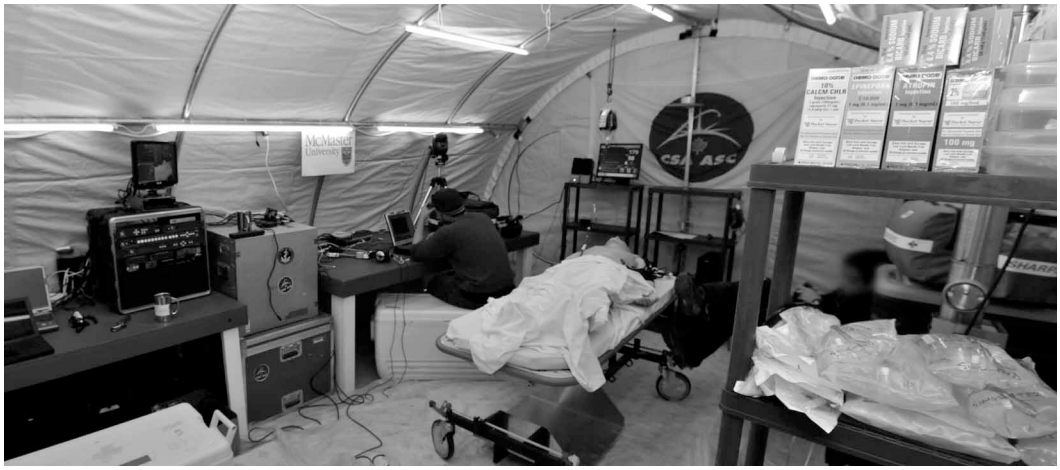


Figure 7 – HMP medical tent interior with the simulator on the stretcher. Left: audio/video equipment rackmount beside simulator control area. Right: medical supplies. (CSBL 2009)

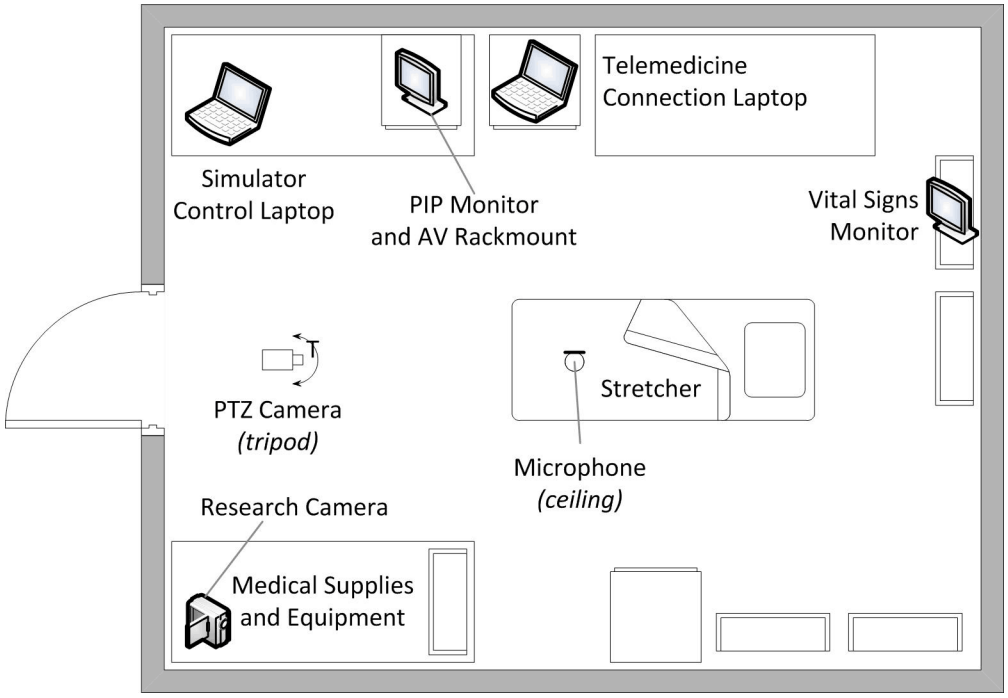


Figure 8 – HMP medical tent interior picturing audio/video layout. PTZ = pan-tilt-zoom. PIP = picture-in-picture. A/V = audio/video.

Figure 9 – Mauna Kea research base simulation tent interior. Left: audio/video and networking rackmount. Centre: simulator on stretcher with vital signs monitor. Right: medical supplies. (CSBL 2010)

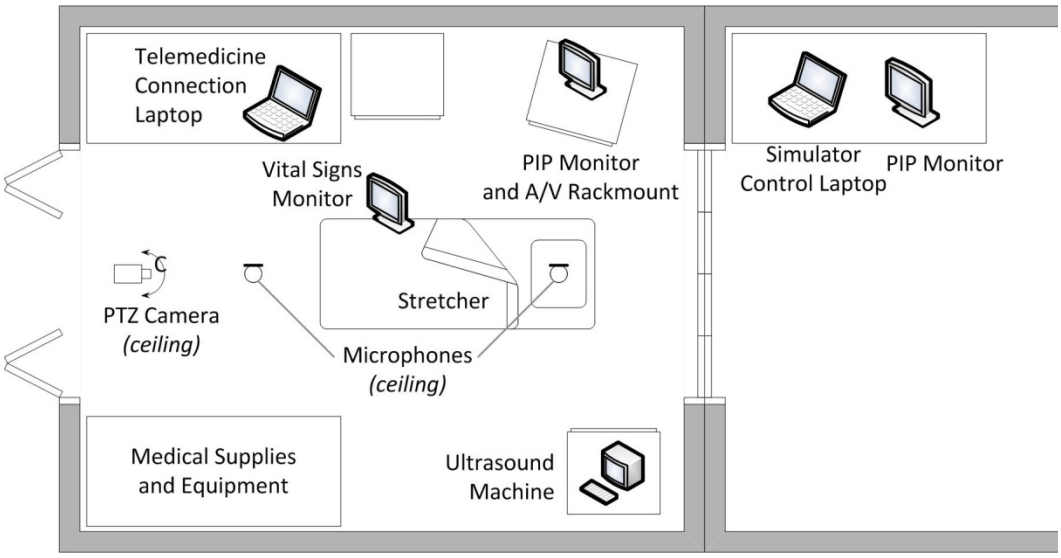


Figure 10 – Mauna Kea research base simulation tent interior picturing audio/video layout. Simulator control area on right side of image in adjacent medical tent. PTZ = pan-tilt-zoom. PIP = picture-in-picture. A/V = audio/video.

3.6.2 Medical equipment and supplies

Pre-selection of appropriate medical equipment and supplies to be used at the field sites were dictated by the scope of the medical conditions simulated and level of training provided to the participants. Shipping and simulation limitations, however, restricted the quantity of the selected medical equipment and supplies. Certain supplies, such as IV catheters, had to be reused to maintain adequate stock for subsequent simulations. Examples of equipment include a full airway kit (e.g. oral and nasal airways, laryngoscope, ET tubes), AED, ACLS drugs (e.g. epinephrine, atropine), IV equipment and fluids, and personal protective equipment. A comprehensive list is provided in Appendix A.

Lessons learned from Devon Island prompted the assembly of a kit mock-up simulating the content of a typical International Space Station (ISS) Advanced Life Support Pack (ALSP) to be used on Mauna Kea (Figure 11). This expanded the formulary to include additional medications such as morphine, as well as additional equipment such as a manual suction device, and IV pressure infuser.

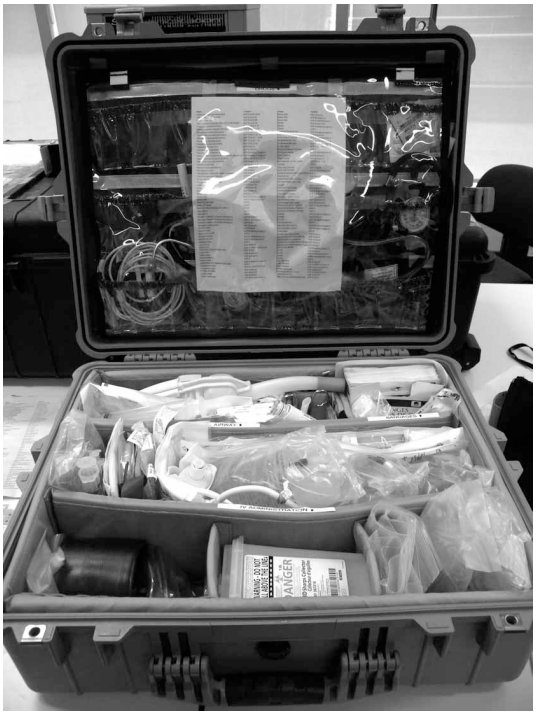


Figure 11 - Simulated International Space Station Advanced Life Support Pack. (CSBL 2010)

3.6.3 Simulation systems

Two different high-fidelity patient simulators were used on Devon Island (SimMan) and Mauna Kea (SimMan 3G). While adding complexity, it allowed us to test both systems with their individual functionalities, while maximizing the breadth of experience gained from the two deployments.

SimMan (Laerdal Medical AS, Stavanger, Norway) was deployed on Devon Island. This is a pneumatically-driven, tethered manikin fed by an external air compressor. Specifically configured for the field, the manikin was controlled by a

Panasonic Toughbook 30 laptop (Panasonic Corporation, Osaka, JP) connected through an intermediate "Linkbox". The control laptop was running Laerdal's control software SimMan v3.4 (Figure 12).

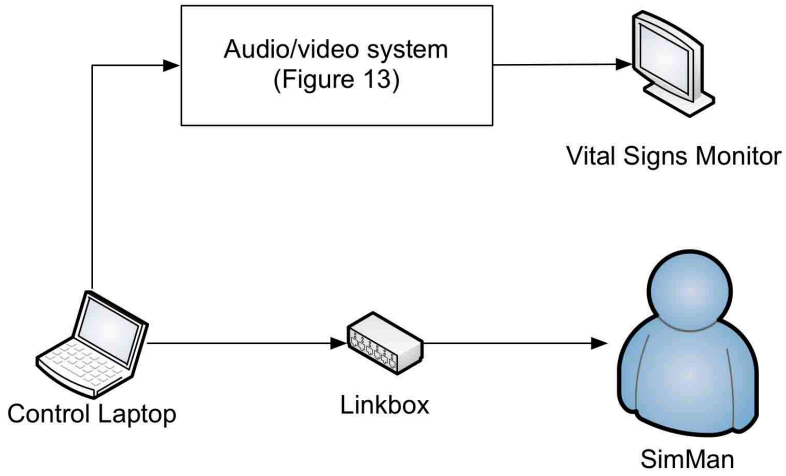


Figure 12 – SimMan control system diagram. Control laptop sends command output and audio through the Linkbox to SimMan. External display output is routed through an audio/video capture system before being displayed for participants on a vital signs monitor.

SimMan is capable of generating chest rise and fall, palpable carotid, radial, and femoral pulses, breath, heart, bowel, and pre-recorded or operator-produced vocal sounds. Advanced airway management interventions, including cricothyrotomy and chest tube insertion, are possible in response to tongue swelling, tracheal obstruction, and trismus. A dedicated IV arm allows for the insertion of an IV line for fluid and medication administration. A blood pressure arm allows for blood pressure assessment using a simulated blood pressure cuff

by auscultation or palpation. Finally, the simulator generates ECG rhythms though preplaced electrode attachment points and is able to be defibrillated.

On Mauna Kea, the next generation SimMan 3G (Laerdal Medical AS, Stavanger, Norway) was deployed. This simulator's capabilities are similar to SimMan in most respects. The most notable difference is the Ethernet connectivity possible over an Ethernet or wireless (Wi-Fi) local area network (LAN) or direct Wi-Fi connection between the Dell Latitude XT control laptop (Dell Inc., Round Rock, TX) and the manikin. Extra mobility is achieved by using on-board battery packs and an internal compressor. Furthermore, the manikin has a pre-placed IV catheter, full pupil reactivity, can convulse, and displays cyanosis through two blue light emitting diodes inside its mouth. In this case, the control laptop was running Laerdal's control software SimMan 3G v1.1. A full list of both simulators' capabilities is provided in Appendix B.

In addition to "real" vital signs, both control laptops output virtual vital signs to an attached monitor as an extended desktop. This configurable monitor displays ECG, oxygen saturation (SpO_2), expired carbon dioxide and arterial blood pressure waveforms, alongside heart rate, respiration rate and temperature values. These waveforms are triggered to display by the simulator operator with the exception of SimMan 3G's SpO_2, which is automatically triggered by the placement of a simulated pulse oximeter.

3.7 AUDIO, VIDEO, AND TELEMEDICINE NETWORKS

3.7.1 Simulation and telemedicine networks

Running and monitoring the simulations required a functionally discrete audio/video network from the telemedicine network, despite both sharing several common components (Figure 13 and Figure 14). The primary goal of the simulation network is threefold: 1) to control the simulator, 2) output the virtual vital signs to a monitor, and 3) provide enough situational awareness to the operator to be able to appropriately manipulate the simulator's physiologic state.

First, the two simulators were controlled multiple configurations. SimMan could only be controlled through a serial connection to an intermediate "Linkbox" that connected to the manikin via a parallel connection. In contrast, SimMan 3G was connected by an Ethernet cable to Mauna Kea's LAN. Network restrictions imposed by IT staff allowed only two simulations to be conducted through a direct Wi-Fi connection to SimMan 3G

Second, all virtual vital signs were output in the simulation tent, as well as being transmitted to the teleprovider by using a Kramer PIP-300 picture-in-picture inserter (Kramer Electronics, Jerusalem, Isreal) to place them over a background image of the interior of the simulation tent. A Kramer VP-701XL digital scan converter (Kramer Electronics, Jerusalem, Isreal) was required to convert the digital image into an analog signal for picture-in-picture insertion. Vitals signs

were available to the participants on a second Elo 1522L touchscreen monitor (Elo TouchSystems, Menlo Park, CA) through a video graphics array (VGA) connection from the digital scan converter as an extended desktop of the control laptop.

Finally, situational awareness was obtained by simply duplicating the image transmitted to the teleprovider. A tripod (Devon Island), or ceiling (Mauna Kea) mounted Sony EVI-D70 pan-tilt-zoom (PTZ) camera (Sony Corporation, Tokyo, Japan) observed the entire scene and was manipulable on verbal command by the teleprovider. Audio was captured by one (Devon Island) or two (Mauna Kea) ceiling mounted Sony ECM-674 shotgun electric condenser microphones (Sony Corporation, Tokyo, Japan). Video was combined with audio in a MOTU V3HD Firewire converter (MOTU, Cambridge, MA) to the MacBook Pro telemedicine laptop (Apple, Cupertino, CA). All video and audio was recorded using a Sony HVR-M15AU high definition video (HDV) (Sony Corporation, Tokyo, Japan) onto miniDV tape.

The telemedicine connection was made possible through one of two configurations:

1. A teleconference link established over Skype's proprietary Voice-over-IP protocols (Skype Technologies S.A., Luxembourg, Luxembourg) using Skype version 4.0. Video was transmitted at 30

frames per second (fps) at 640x480 VGA resolution with MPEG-4 video encoding.

2. The Data Redistribution System (DRS), a Canadian Space Agency configured and controlled web-accessible Axis video server (Axis Communications AB, Emdalavgen, Sweden) with end-user defined frame rate and display resolution with MPEG-4 video encoding. Up to four composite video streams were accessible at one time including two remotely controllable ceiling-mounted IP cameras.

Figure 13 – HMP audio/video (A/V) system diagram. Vital signs are output from the simulator control laptop and converted from digital to analog format for picture-in-picture (PIP) insertion over a background image captured by a pan-tilt-zoom (PTZ) camera. The compiled image is then combined with audio and converted to a Firewire output to the telemedicine connection. This output is also captured by a digital video (DV) tape deck.

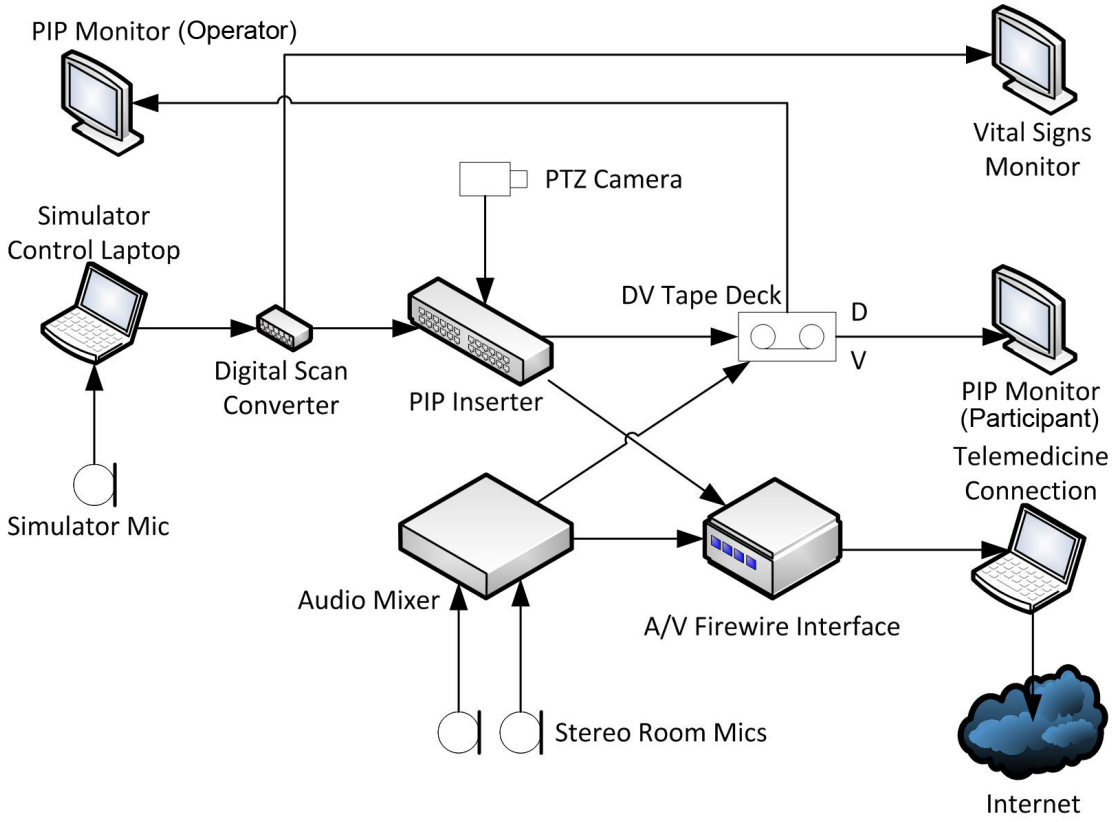


Figure 14 – Mauna Kea audio/video (A/V) system diagram. This system is functionally similar to the HMP audio/video system (Figure 13) for picture-in-picture (PIP) insertion. Note the addition of an audio mixer for multiple microphone input and digital video (DV) tape deck output to a second picture-in-picture (PIP) monitor for remote simulator control.

3.8 FIELD SITE INFORMATION TECHNOLOGY NETWORK

Field site IT networks were set up in a similar way to a typical enterprise-grade network. Each operations and research tent was equipped with a D-Link DES3526 24-port 10/100 Mbps L2 network switch with 8.8 Gbps bandwidth (D-Link Systems Inc., Fountain Valley, CA) to which multiple computers could be connected. Each switch port was assigned a unique static public IP address. Limited wireless connectivity was available through a number of 802.11g wireless routers distributed throughout the camps.

At both sites, high-speed Internet connectivity was only possible through a C-band (4-8 GHz) or Ka-band (26.5-40 GHz) satellite uplink to the Anik F2, a geostationary communications satellite. Other research activities and the cost of satellite usage restricted our bandwidth use to a maximum of 3 Megabits per second (Mbps) combined upload and download.

3.9 TECHNICAL SOLUTIONS

3.9.1 Ability to remotely operate simulator

To maintain the integrity of the simulation environment, certain requirements must be met. The simulator operator must be able to see the remote medical team, interact with the simulator control panel to adjust physiologic parameters, and transmit audio through the simulator and computer to interact

with the participants and teleprovider for debrief. Furthermore, the participants must be able to access all simulator capabilities including the vital signs monitor.

While the SimMan 3G has built in capability to be operated over a TCP/IP network, the tethered SimMan used on Devon Island has no such capacity. Three options were considered:

1. Create a **virtual serial port** on the remotely operating computer terminal that would send and receive manikin information over TCP/IP from the control laptop's serial port as if it were directly connected. Virtual serial port forwarding has the disadvantage of preventing the participants from viewing the vital signs monitor since the control laptop would not output video in this configuration.
2. Use **virtual network computing (VNC)** to transmit mouse and keyboard events to the control laptop while receiving video output. This option would require advanced router and firewall configuration of the field site network.
3. **Remote application sharing**, based on International Telecommunications Union (ITU-T) protocol T.128 for multipoint application sharing has the added advantage of allowing the simulator operator to initialize the simulator and control software instead of the field site.

Ultimately, option 3 was selected as a solution for a number of reasons. Remote control of the control laptop was established through a Microsoft RDC (Microsoft Corporation, Redmond, WA) that uses the Remote Desktop Protocol (RDP v6.1), which is based on a modified T.128 protocol. The ubiquity of the RDP on all Windows-based systems eliminated the need for software installation and minimized setup effort on the manikin's end. Being a commonly used protocol integrated in the Windows operation system (OS) simplified the task for users on both ends to bypass their OS firewall and for system administrators to forward the required ports through the network firewall.

One simulation on Devon Island was remotely operated at a distance of 3000 km from McMaster University (Hamilton, Canada). The simulator operator made a RDC to the control laptop with a webcam-enabled Skype connection providing situational awareness, while a separate Skype connection was made on the telemedicine laptop (Figure 15). An experienced simulation instructor at the same location as the remote operator also observed the simulation. To facilitate the debriefing session, communication using microphones and speaker output was established via a Skype connection to each respective party with the field site acting as a hub.

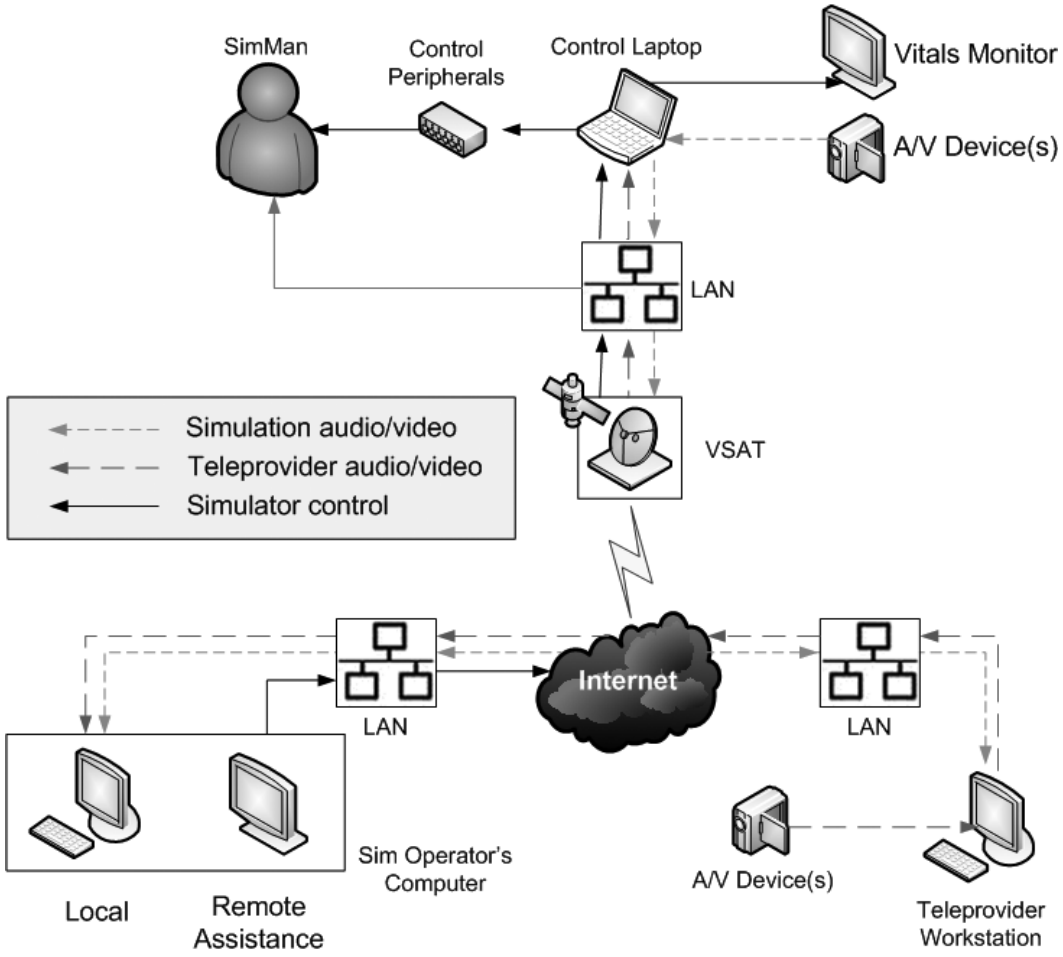


Figure 15 – Telecommunication and simulator control flow diagram. Audio/video of the simulation is distributed to both the remote simulation operator and teleprovider (short dashed line). Teleprovider audio/video is distributed to the simulation site and remote simulation operator (long dashed line). SimMan control is either direct from the control laptop, through the field site's local area network, or from the remote simulator operator (solid line).

3.9.2 Effect of time delay

A commercial, off-the-shelf IP network emulation software, NetDisturb (OMNICOR, Foster City, CA), was used to introduce a 4 second round-trip time delay during 3 of the simulations. This level of delay is roughly equivalent to the delay one might expect in direct station-to-station Earth-Moon radio communications. This can be calculated by dividing the distance of the moon (384,400 km) by the speed of light (3×10^8 m/s), which is approximately 1.3 seconds, while accounting for additional ground network and encoding/decoding processing time (~2-3 s) (Larson and Pranke 1999).

The IP network emulation software resided on a dedicated Veriton X270 computer desktop (Acer America Corporation, Mississauga, ON), containing two 100 Gigabit Ethernet network interface cards, which acted as an intermediary connection between the telemedicine laptop and the field site's LAN. All network packets passing to and from the telemedicine laptop were essentially held in the NetDisturb computer's random access memory (RAM) for a user-determined period of time, between 0 ms and 9,999 ms.

3.9.3 Feasibility of progressive simulations

The wireless control capability of SimMan 3G and extra mobility allows the simulator to be easily setup outside of a customized simulation environment, but more importantly moved during the course of a simulation. These features

allowed us to test the feasibility of running a progressive medical simulation beginning with an acute medical crisis in the field that required extraction to the simulation tent for continuing medical care. Two progressive medical simulations were preceded by a field test of the simulator and equipment on a modified ARGO (ARGO, New Hamberg, ON) on-site medical transport vehicle. This vehicle was not used during the simulations.

Connection to the simulator was obtained through a direct wireless link, not through the camp's wireless network. The telemedicine link was extended outside of the simulation tent by using a CSA-provided head-mounted camera attached to one of the participants. This two-way audio, one-way video link was broadcast into the simulation tent to a dedicated head-mounted camera computer. Audio/video was then re-transmitted to the teleprovider by placing a PTZ camera on the computer monitor displaying the head-mounted camera video output, and the telemedicine laptop microphone by the computer's speakers. The head-mounted camera also served to provide situational awareness to the simulation operator.

4 RESULTS

All simulations, except one, were executed successfully with minor alterations of the initial simulation plan during the simulation to adapt to unanticipated technological barriers. This chapter will begin with an analysis of the technical failures that impacted the simulations and their sources; followed by the participants' impressions of the audio/video and simulation quality; and concluding with the specific challenges encountered while running simulations remotely, with artificially introduced time delays, and while moving from one location to another. While not the focus of this study, it should be noted that when asked during the debrief, all teleproviders and participants commented positively on the perceived realism of the simulations.

4.1 CRITICAL EVENTS

All video recordings of the simulations were reviewed for the presence of technical failures that resulted in critical events. A critical event is defined as an unanticipated interruption or distortion of the simulation that is incongruent with the intended medical scenario. For comparison, these technical failures were broken down and categorized by system into the following 5 groups (Figure 16):

1. **Audio** disruptions between the teleprovider and participants through the telemedicine network.

2. **Video** disruptions between the teleprovider and participants through the telemedicine network.
3. Network **connection** issues between the teleprovider and participants, not including audio or video disruptions caused by network instability.
4. **Simulator** and related peripheral equipment failures, and improper interaction with the simulator by participants.
5. Medical **equipment** or supplies whose operation is inconsistent with the simulation, or failure of the medical supplies to work as intended by the manufacturer.

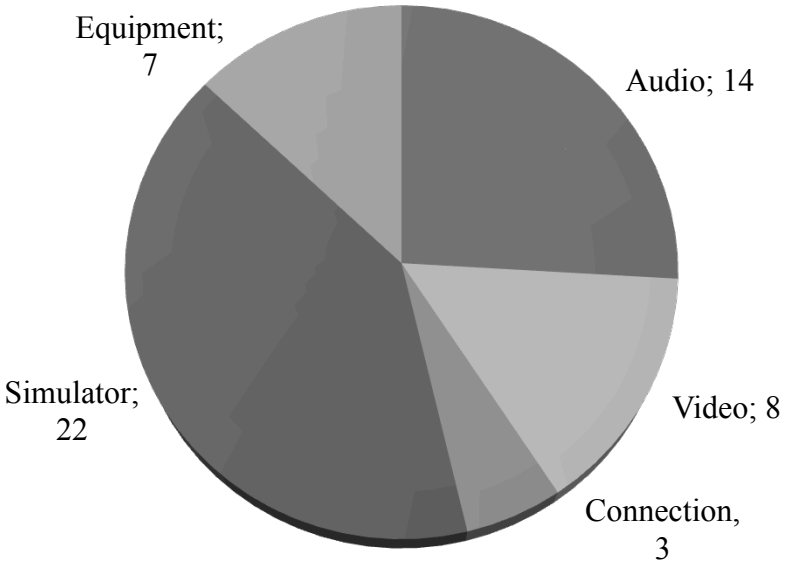


Figure 16 – Total number of critical events by source.

4.1.1 Number and nature

A number of technical glitches resulted in critical events, as would be expected when field-testing new equipment configurations in such austere environments. Every simulation experienced at least one critical event (**Table 2**), fortunately, only one simulation had to be terminated following one of these events. The completed simulations were executed as planned, or with slight modifications in the flow of the scenario to align the critical event so that it made medical sense.

The interrelated nature of the sources of critical event precludes any meaningful statistical analysis, as they are not necessarily drawn from independent populations. For example, as the audio and video components of the simulation and telemedicine networks are integrated at some point in the system, an audio-related critical event and video-related critical event may originate from the same underlying technical failure. Comparing these sources as distinct phenomenon would be inappropriate.

A total of fifty-four (54) critical events occurred across the fourteen (14) simulations (Table 2). Most of the critical events occurred as a result of failures originating with the simulator or associated peripheral equipment or use thereof, while the least number of failures occurred with the Internet connection to the teleprovider.

Table 2 – Total number of critical events per simulation.

Date	Simulation	Audio	Video	Connection	Simulator	Equipment
Devon Island, Nunavut						
Jul 17/09	Tele-instruction	6	5	1	1	0
Jul 18/09	Multiple traumatic amputations	3	0	0	1	0
Jul 19/09	AMI[1] to cardiac arrest	0	0	1	1	0
Jul 20/09	AMI[1] to cardiac arrest	1	0	0	1	3
Jul 21/09	Head trauma	0	0	0	1	1
Jul 21/09	Anaphylaxis	2	0	0	1	0
Jul 21/09	Atrial fibrillation to cardiac arrest	0	0	0	0	1
Jul 30/09	Anaphylaxis	1	2	0	1	0
Mauna Kea, Hawai'i						
Jan 30/10	Tele-instruction	0	0	0	3	1
Feb 3/10	Pneumothorax and impaled object	0	0	1	3	0
Feb 5/10	Head trauma	0	0	0	3	0
Feb 5/10	AMI[1]	0	1*	0	0	1
Feb 6/10	AMI[1]	1	0	0	3	0
Feb 7/10	Smoke inhalation	0	0	0	3	0
Total		**14**	**8**	**3**	**22**	**7**

*catastrophic failure resulting in premature termination of the simulation.

1. Audio failures (n = 14) included:
    a. Audio drop-outs (silence) of < 7 seconds
    b. Audio disruption of speech < 1 second
    c. Audio interference < 1 second
2. Video failures (n = 8) included:
    a. Video drop-outs (black screen) < 1 second
    b. Video flickering
3. Connection failures (n = 3) included:
    a. Dropped Skype/DRS connections requiring manual reconnection
4. Simulator failures (n = 22) included:
    a. Disconnection of the control computer from manikin
    b. Failure to connect blood pressure cuff correctly
    c. Pulse oximeter not registering on vital signs monitor once attached; spontaneously disconnecting from vital signs monitor; or displaying “Saturation signal low” on vital signs monitor
    d. Freezing or spontaneous disconnection of the vital signs monitor
    e. Inability to accurately assess a pulse
    f. Inability to accurately auscultate breath sounds
    g. Torn tongue
    h. Leaking intravenous arm despite correct catheter placement

5. Equipment failures (n = 7) included:
    a. Training AED prompts being inconsistent with the simulator's physiologic state
    b. Re-use of medical supplies resulting in breakage
    c. Inability to find, use, or accurately simulate delivery of oxygen

4.1.2 Comparison between Devon Island and Mauna Kea

In contrast to the inability to make comparisons between critical event groups due to the level of interdependence on shared underlying systems, a comparison between the frequency and nature of critical events between field sites is possible as a result of the independent operating conditions and network infrastructure. A one-factor, between-subjects multivariate analysis of variance (MANOVA) was conducted with the five sources of a critical event as the dependant variables, and the two field sites as the independent variables ($\alpha = 0.05$). The test results were significant according to Wilks' Lambda (0.121), $F(5,8) = 11.66$, $p = 0.002$.

Only a significant difference was found between field sites when comparing the simulator as a source of critical events ($F(5, 8) = 12.97$; $p < 0.01$) (Figure 17). Furthermore, video review of the simulations found that roughly one-third (7 of 22 critical events) of the total simulator failures occurred due to the pulse

oximeter (n = 4) and vital sign monitor (n = 3), and that these failures occurred exclusively on Mauna Kea.

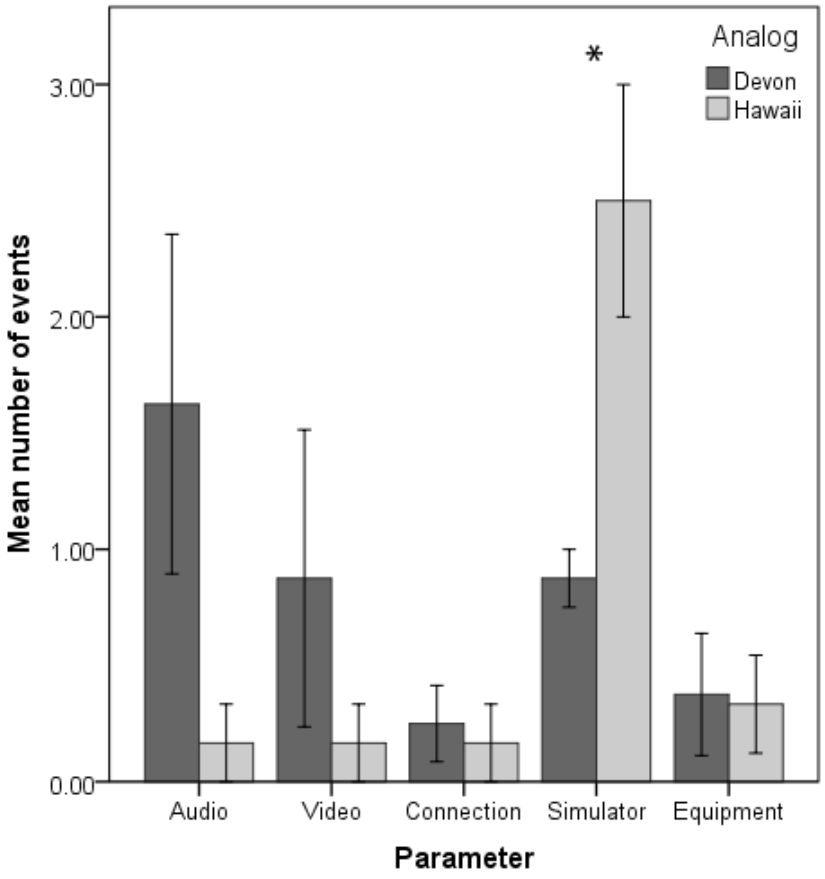


Figure 17 – Mean number of critical events (±*MSE*) occurring during a simulation on Devon Island (dark grey) or Mauna Kea (light grey) caused by audio, video, network connection, simulator, or medical equipment failure. A significantly greater number of critical events occurred in Hawaii due to simulator failure and its associated peripherals.

4.2 AUDIO AND VIDEO QUALITY

During the simulation debrief, all participants and teleproviders were routinely asked to provide their impressions on the influence of the audio/video quality on the ability to manage a medical crisis. All participants found that the video and audio quality were sufficient to adequately supervise the medical simulation (Figure 18). At full 640x480 resolution, teleproviders commented on the clarity of the numbers and waveforms of the vital signs, and ability to recognize medical equipment. Some teleproviders also noted that on occasion the received frame rate was less than 30 fps, however, they also added that this had little effect on their ability to supervise the simulation. Concern was raised, however, on the ability to read fine print when objects were held up to the camera, for example when verifying the name and dosage of a medication. In general, audio quality was also clear and intelligible.

Three (n = 3) of the simulations were supported by CSA's DRS. This was due to the unavailability of the MacBook Pro telemedicine laptop, and inability of the MOTU V3HD Firewire converter to interface with a PC-based computer. Furthermore, when probed during the simulation debrief, teleproviders indicated that only marginal differences were apparent between the video quality of Skype and the DRS.

Figure 18 – Monitoring and recording the video image sent to teleprovider on a 15.4 inch 720x480 LCD display. The video is transmitted to the teleprovider as a color 640x480 image and has been enlarged to fill the teleoperator's monitor while maintaining the original 4:3 aspect ratio. (CSBL 2010)

4.3 NETWORK QUALITY

Over both satellite connections, Skype telecommunication latency was found to range between 500-800 ms. Although this delay had some minor discernable effect on interpersonal communication, it did not appear to effect the progression of any simulation. IT supported bandwidth monitoring at random intervals at both field sites found that audio/video communication over Skype alone never exceeded a peak upload rate of 512 kbps. Use of the DRS, however, frequently exceeded a peak upload rate of 512 kbps per video stream when two or

more video streams were being transmitted. In theory this would allow a maximum of five 640x480 video streams to be sent simultaneously over a 3Mbps satellite link. Continuous monitoring of bandwidth during simulations would provide a more comprehensive assessment of bandwidth use.

4.4 ABILITY TO REMOTELY OPERATE SIMULATOR

From the viewpoint of the participants and teleprovider, the remotely run simulation on Devon Island was successful, without any notable differences from a locally run simulation. On the other hand, the remote operator found that commands sent to the control laptop were delayed and sluggish, and on occasion dropped entirely. This limited their ability to accurately manipulate the simulator's physiologic state in response to events occurring in rapid sequence. Furthermore, vital sign tracings were jittery and slow to update on the operator's end. The network connection, however, remained stable, and situational awareness through the PTZ camera was sufficient to respond appropriately to medical interventions performed on-site.

The teleprovider, simulation instructor, and participants all commented positively on the quality of the audio connection and ability to conduct a thorough and complete debriefing session.

On Mauna Kea, several attempts were made to remotely operate SimMan 3G over the Internet using its native control software without success. The time to connect was approximately 2 mins, but even when it appeared to have connected the software seemed unable to render any of the control parameters, displaying instead a simple white-filled window. At artificially introduced latencies of >800 ms, no connection was possible even after waiting 15 mins.

4.5 EFFECT OF TIME DELAY

Some difficulty was encountered while initiating a Skype connection at artificially introduced round-trip latencies of 4 seconds. Several attempts were made before obtaining a successful connection, however, it was not apparent under what conditions a successful connection would be more likely to succeed. It was also not possible to make a connection without the artificial time delay and then increase the delay, as that would sever the connection. Once a connection had been made, however, it remained stable throughout the duration of all 3 simulations.

Video quality appeared to be significantly reduced with 4 s round-trip latencies. Teleproviders commented on their inability to read ECG tracings, and were not able to recognize ventricular tachycardia from another arrhythmia because of the degraded video quality. Skype also reported outgoing display

resolution to be at one-half normal (320x240), and at one-third normal frame rate (10 fps). Fortunately, audio quality remained unaffected.

4.6 FEASIBILITY OF PROGRESSIVE SIMULATIONS

Range tests conducted on Mauna Kea of the SimMan 3G mounted on the ARGO (Figure 19), located in the field and within the simulation tent found that the maximum stable software connection was possible up to approximately 75 m. Connection stability was highly dependant on the distance between the laptop and the manikin, number and proximity of intervening bodies, presence of volcanic dust in the air surrounding the manikin from the ARGO while in motion, and presence of intervening electromagnetic field generating equipment (Figure 20).

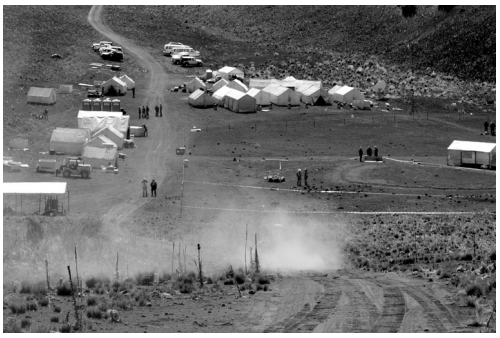
A)  B) 

Figure 19 – Wireless range testing. A) Strapping the manikin to a modified ARGO vehicle for patient transport. B) Dust enveloping the ARGO while in motion.(CSBL 2010)

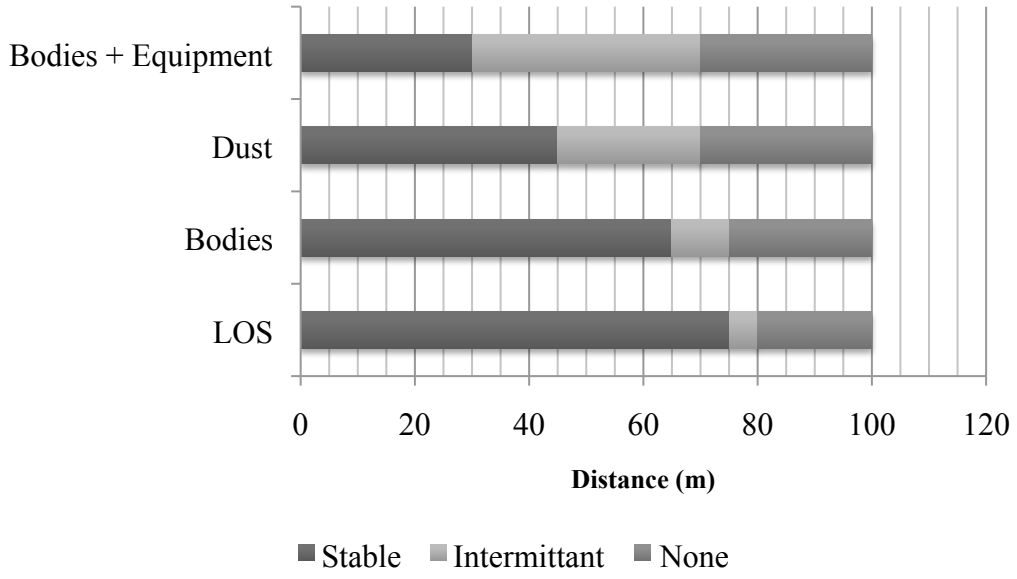


Figure 20 – Approximate range (in meters) of wireless software connectivity under different operating conditions. SimMan 3G connectivity was stable (dark grey), intermittent (light grey), or dropped without the possibility of reconnection (medium grey) under four environmental conditions between the control laptop and manikin: 1) intervening bodies and equipment emitting electromagnetic interference; 2) clouds of volcanic dust surrounding the manikin; 3) intervening bodies only; and 4) clear line-of-sight (LOS).

Once the simulator had been transported into the medical tent on a stretcher, the simulation progressed smoothly. Outside, however, the teleprovider was forced to rely on the head-mounted camera for two-way communication and situational awareness. This proved to be a challenge as a result of severely reduced video and audio quality. First, the head-mounted camera naturally produces an image at a reduced resolution of 320x240 at 10 fps. Combined with the additional compression through Skype, and frequent head movements from the participant, video was practically unusable. Interestingly, audio quality was clear in the

simulation tent, but experienced degradation when being re-transmitted to the on-site participant. Audio from the participant to the teleprovider remained clear across the network.

Finally, the wireless manikin control connection dropped once, but was reestablished without any noticeable effect on the simulation. However, audio quality through the manikin was very poor, jittery and unintelligible at range, but cleared once the manikin was in the simulation tent.

5 DISCUSSION

This report describes an investigation into the technical requirements supporting the use of high-fidelity patient simulation for telemedicine research. The ability to replicate the management of acute medical emergencies in a risk-free setting enables the exploration of telemedicine technology and systems in this domain using a controlled, methodical approach. Improving telemedicine systems and bringing this educational modality to remote and rural communities may have a profound impact in the accessibility and quality of healthcare in these regions.

It is important to disclose that all data was collected in an operational environment, not under experimental conditions. All phenomenon discussed here would benefit from additional study in controlled conditions to determine the extent and significance of their effect on medical simulation and telemedicine activities. Furthermore, the interpretation of the video recordings and discussion with participants and teleproviders was conducted exclusively by the investigators of this research, with some input from external bodies and subject matter experts.

5.1 A/V AND IT TECHNOLOGIES

First, not enough emphasis can be placed on the importance of thorough preparation before going into the field. The success of any simulation, especially in support of telemedicine research, depends solely on the ability of each

component of a highly complex network of discrete systems to work in synchrony. While it is impossible to replicate every condition that is present in the field, each system configuration should be connected and tested in a laboratory environment. Ideally, this would be done with the exact pieces of equipment that are to be used in the remote environment. As an example of the importance of this concept, an experience on Devon Island quickly revealed that the DV tape deck brought to the Arctic appeared visually similar to the tested DV tape deck, but in fact had a different type of Firewire input connector, for which the correct cable was unavailable.

Setting up the A/V and IT network also posed a challenge. Close collaboration with the IT support staff for the field site months in advance ensured that the simulator integrated seamlessly with the network and that our bandwidth requirements were met. Despite this level of preparation, significant time was spent with the support staff to integrate the SimMan 3G into the wireless network without success. Upon further investigation in the lab, the problem could not be replicated, and wireless network integration was made without any issues. Furthermore, connectivity issues were experienced using the DRS, with many teleproviders unable to connect. It is theorized that firewall security at the CSA or on the teleproviders end posed a major barrier.

5.1.1 Video resolution and bandwidth

In contrast to the DRS, Skype was found to be a high quality, accessible, low-cost replacement for commercial video conferencing systems. Minimal setup is required on both ends of the telemedicine link, and no firewall configuration was necessary. With Skype's continual development, 720p high-definition video conferencing with up to 5 people simultaneously is now possible. This may further facilitate distributed multi-party participation in remotely operated and instructed medical simulation. This feature may also be a solution to the degraded audio and video quality experienced during the progressive simulation, by avoiding the retransmission of audio and video from the teleprovider to the participant.

All things being equal, it is safe to say that higher video resolution is always "better", but in what way, and to what extent would it impact the quality of the medical simulation or educational event? More importantly, higher resolution equates to greater bandwidth use, a precious commodity in remote and rural areas. Our experiences on Devon Island and Mauna Kea show that telemedical support of simulated medical emergencies is reasonable at a resolution of 640x480 and 30 fps with video compression. Bandwidth measurements indicate that at this resolution and frame rate, each video stream consumes roughly 512 kilobits per second (kbps) of upload bandwidth. Additional studies need to be conducted to

determine the impact of video resolution on the quality of care and the optimal tradeoff between resolution and bandwidth use.

5.1.2 The effect of network latency

It was also very apparent that the network quality significantly affected the ability to successfully maintain a telemedicine link and run successful simulations. The introduction of an artificial time delay into the telemedicine network severely reduced the video quality of the Skype connection. This may be due to the innate adaptive nature of the software attempting to maintain a stable connection by sacrificing video quality (Hossfeld, et al. 2005).

We also found that despite the built-in capability for SimMan 3G to be operated remotely over a LAN, it was impossible to do this through a virtual LAN created over a satellite connection. As the ability to connect worsened with increasing artificial time delay, it is possible that the inherent latency in communicating with a geostationary satellite was enough to prohibit a stable connection. While remotely operating SimMan using a RDC was successful, the operating conditions were not ideal, resulting in sluggish and unresponsive commands. This may also be a result of the natural satellite communication latencies of 400-800 ms. One solution to this may be to preprogram the scenario to reduce the amount of intervention required by the simulator operator.

5.1.3 Environmental impact on wireless network stability

When conducting progressive simulations, special attention should be paid to the impact of natural and anthropogenic environmental factors on the stability of a wireless network. SimMan 3G is documented as having a maximum operating range of 100 m (Laerdal Medical AS 2009), but clearly this must be under ideal conditions as the maximum range we found for a stable connection was 75 m. This range decreased as operating conditions deteriorated. This may be explained by the absorption or reflection of radio waves by the high magnetic mineral content of the volcanic dust (Morris, et al. 2001), presence of metal and electromagnetic field producing A/V equipment, and living tissue (Bertoni 1999). Every effort should be made to conduct an analysis of the operating environment prior to conducting a progressive simulation to adjust the maximum operating range of SimMan 3G so the simulation can be conducted without connection interruptions.

5.2 CRITICAL EVENTS

Every simulation experienced at least one critical event that interrupted or altered its flow. This was expected given the complexity and novelty of the systems and their environment. Unfortunately, the interdependence of each component makes it virtually impossible to determine the source of any given critical event. This is especially true of the audio and video interruptions, which

could have failed because of equipment malfunctions or mishandling, environmental disruptions, or poor network conditions. To prevent these in the future, thorough testing and preparation in the lab setting is crucial. One method to avoid network disruptions is to ensure a high Quality of Service (QoS) for research applications. This would require extensive network configuration and close collaboration with field site IT staff.

An interesting result was the significantly higher incidence of critical events due to simulator failure on Mauna Kea than on Devon Island. The most obvious difference between the two sites was the use of SimMan 3G on Mauna Kea versus SimMan on Devon Island. This recently released model of simulator may not have been as extensively field-tested by end-users as the older SimMan model. Furthermore, the collective expertise in its use and configuration was much less than for SimMan. Nevertheless, several of the failures resulted from improper use of the ancillary medical equipment such as the blood pressure cuff. These events could be mitigated in the future by a more thorough and structured orientation to the simulator prior to the medical simulation.

Finally, equipment failures accounted for a portion of the critical events. Half of these were due to the training AED giving incorrect prompts, for example trying to defibrillate a patient with a pulse. While the AED allowed for the selection of appropriate patient states prior to the simulation, it was impossible to

predict at what patient state and what stage of the simulation the AED would be operated. Designing a simulated AED that "talks" to the simulator, or using a remotely operated training AED could overcome these inconsistencies. It also became clear that having a clearly labeled and functioning oxygen delivery system is vital as all simulations required oxygen therapy, and the lack of such a system caused confusion and disorientation among participants and teleproviders.

5.3 CONCLUSION

In conclusion, running high-fidelity patient simulation in extreme environments with remote medical support is technically feasible. Under certain circumstances it is also possible to remotely operate and instruct a simulation, artificially introduce a time delay over a telecommunication network, and run a progressive simulation. The extreme variability in operating conditions, however, demands further investigation into each phenomenon to elicit the precise technical requirements and operating conditions that produce the most reliable and accurate simulations. These results also highlight the importance of rigorous pre-deployment system testing, close collaboration with IT support, and an appreciation of the effect of unreliable network conditions on teleconferencing connections. Nevertheless, it is clear from these early results that high-fidelity simulation holds the potential to unlock new and exciting findings in acute care telemedicine research.

BIBLIOGRAPHY

4) Berg, Benjamin, Lorrie Wong, and Dale Vincent. "Teaching nursing skills at a distance using a remotely controlled human patient simulator." *J Telemed Telecare* 13, no. suppl. 3 (2007): 17-19.

5) Bertoni, H.L. *Radio Propagation for Modern Wireless Systems.* Upper Saddle River, NJ: Prentice Hall Professional Technical Reference, 1999.

6) CERMUSA. *Patient Simulator at a Distance.* 2008 йил 28-Mar. http://www.youtube.com/watch?v=x25Ih_sUoas.

7) Cooper, J, and V Taqueti. "A brief history of the development of mannequin simulators for clinical education and training." *Qual Saf Health Care* 13, no. suppl. 1 (Oct 2004): 11-18.

8) CSBL, Centre for Simulation-Based Learning. McMaster University, Hamilton.

9) CSBL, Centre for Simulation-Based Learning. McMaster University, Hamilton.

10) Google Inc. *Google Maps.* 2010. http://maps.google.com (accessed 2010 йил 9-7).

11) Haskins, Paul, David Ellis, and James Mayrose. "Predicted utilization of emergency medical services telemedicine in decreasing ambulance transports." *Prehospital Emergency Care: Official Journal of the National Association of EMS Physicians and the National Association of State EMS Directors* 6, no. 4 (2002): 445-8.

12) Havel, Christof, et al. "Quality of closed chest compression in ambulance vehicles, flying helicopters and at the scene." *Resuscitation* 73, no. 2 (2007): 264-270.

13) Holcomb, John, et al. "Evaluation of trauma team performance using an advanced human patient simulator for resuscitation training." *The Journal of Trauma* 52, no. 6 (2002): 1078-85; discussion 1085-6-1078-85; discussion 1085-6.

14) Hossfeld, Tobias, Andreas Binzenhofer, Markus Fiedler, and Kurt Tutschku. *Measurement and analysis of Skype VoIP traffic in 3G UMTS systems.*

Institute of Computer Science, University of Wurzburg, Wurzburg: University of Wurzburg, 2005.

15) Hu, Y, and V Li. "Satellite-based internet: a tutorial." *IEEE Communications Magazine* 39, no. 3 (2001): 154-162.

16) Hurst, Victor IV, Harold K Doerr, James D Polk, Josef Schmid, Scott Parazynksi, and Scott Kelly. *Integrated clinical training for space flight using high-fidelity patient simulator in a simulated microgravity environment.* Technical Report, NASA Johnson Space Center, Houston: NASA, 2007.

17) Karlsten, R, and B Sjoqvist. "Telemedicine and decision support in emergency ambulances in Uppsala." *J Telemed Telecare* 6, no. 1 (2000): 1-7.

18) Kyle, Richard, and Bosseau Murray. "Topic 15: Location, Location, Location." *Clinical Simulation: Operations, Engineering and Management* (Elsevier Inc.), 2008: 553-565.

19) Laerdal Medical AS. *SimMan 3G Directions for Use.* Tanke Svilandsgate 30: Laerdal Medical AS, 2009.

20) —. *SimMan Directions for Use.* Tanke Svilandsgate 30: Laerdal Medical AS, 2009.

21) Larson, W J, and L K Pranke. *Human Spaceflight: Mission Analysis and Design.* New York, NY: McGraw-Hill, 1999.

22) Mathews, Kate, Mark Elcock, and Jeremy Furyk. "The use of telemedicine to aid in assessing patients prior to aeromedical retrieval to a tertiary referral centre." *Journal of Telemedicine and Telecare* 14, no. 6 (2008): 309-14.

23) Meade, Brian, and Peter Barnett. "Emergency care in a remote area using interactive video technology: a study in prehospital telemedicine." *Journal of Telemedicine and Telecare* 8, no. 2 (2002): 115-7.

24) MedSMART, Inc. *MedSMART, Inc.* 2009. http://www.med-smart.org/.

25) Morgan, Pamela J, and Doreen Cleave-Hogg. "A worldwide survey of the use of simulation in anesthesia." *Can J Anaesth* 49, no. 7 (2002): 659-62.

26) Morris, R.V, et al. "Phyllosilicate ‐ poor palagonitic dust from Mauna Kea Volcano (Hawaii): A mineralogical analogue for magnetic Martian dust?" *Journal of Geophysical Research Planets* 106, no. E3 (2001): 5057-5083.

27) Musson, D.M. "The use of high-fidelity patient simulation in defining telehealth support needs for in-flight medical crisis management in long duration spaceflight." *58th International Astronautical Congress* IAC- 07-A1.8.0f. (2007).

28) Ricci, Michael, Michael Caputo, Peter Callas, and Mary Gagne. "The use of telemedicine for delivering continuing medical education in rural communities." *Telemedicine Journal and E-Health: The Official Journal of the American Telemedicine Association* 11, no. 2 (2005): 124-9.

29) Rogers, F, et al. "The use of telemedicine for real-time video consultation between trauma center and community hospital in a rural setting improves early trauma care: preliminary results." *The Journal of Trauma* 51, no. 6 (2001): 1037-41.

30) Small, S, R Wuerz, R Simon, N Shapiro, A Conn, and G Setnik. "Demonstration of High-fidelity Simulation Team Training for Emergency Medicine." *Academic Emergency Medicine* 6, no. 4 (1999): 312-323.

31) STARS. *STARS Human Patient Simulator Program.* 2004.

32) Terkelsen, Astrid, Jens Nielsen-Kudsk, Henning Andersen, and Jens Lassen. "Telemedicine used for pre-hospital diagnosis of a patient with acute pulmonary embolism." *Ugeskrift for Laeger* 170, no. 9 (Feb 2008): 753-753.

33) von Lubitz, DKJE, et al. "Simulation based medical education: Advanced distributed learning as a tool for the future." Jun 2002.

34) Wright, Stewart, et al. "High fidelity medical simulation in the difficult environment of a helicopter: feasibility, self-efficacy and cost." *BMC Medical Education* 6, no. 1 (2006): 49-49.

APPENDIX A – MEDICAL SUPPLIES AND EQUIPMENT

Medical supplies on Devon Island

1. Sharps bin and lid
2. Simulated blood bags (6 bags)
    a. O Negative (x3)
    b. O Positive
    c. A Positive
    d. A Negative
3. Large Gloves (1 box)
4. Sterile Gloves
    a. Size 7 (x3)
    b. Size 8 (x4)
5. Endotracheal tubes (7.0 & 8.0)
6. Cricothyrotomy kit
7. Airway kit
    a. Nasopharyngeal airways (large and small)
    b. Oropharyngeal airways (5 sizes)
    c. Laryngoscope
    d. Miller laryngoscope blade (size 3)
    e. Macintosh blades (sizes 3 and 4)
    f. Laryngeal mask airway (4.0)
    g. Reinforced endotracheal tube (7.0)
    h. Stylette
    i. CO_2 detector (2)
    j. Syringe (20cc)
    k. Ambubag
    l. Tape
8. 1000 mL 0.9% NaCl IV bags (4)
9. 500 mL 0.9% NaCl IV bags (2)
10. 100 mL 0.9% NaCl IV bags (8)
11. IV infusion kit
    a. IV administration sets
    b. 18.5 gauge blunt needles
    c. IV catheters (6 x 22G, 1 x 20G)
    d. 60mL syringes (3)
    e. 3mL syringe
    f. Tourniquet
12. Simulated preloaded resuscitation drugs
    a. Atropine (10)

    b. Epinephrine (10)
    c. Lidocaine (10)
13. 4x4 gauze sponges
14. Alcohol wipes
15. Stethoscope
16. Non-rebreather mask

Medical supplies on Mauna Kea

1. Simulated medications
    a. Haloperidol Injectable (Haldol)
    b. Furosemide Injectable (Lasix)
    c. Epinephrine Cardiac (Adrenaline)
    d. Meperidine Injectable (Demerol)
    e. Phenytoin Injectable (Dilantin)
    f. Propanolol HCl (Inderal)
    g. Lidocaine/Cardiac (Xylocaine/Cardiac)
    h. Atropine Injectable
    i. Adenosine Injectable (Adenocard)
    j. Verapamil Injectable (Isoptin)
    k. Diazepam Injectable (Valium)
    l. Lidocaine Plain (Xylocaine Plain)
    m. Morphine Injectable
2. Simulated preloaded resuscitation drugs
    a. Epinephrine
    b. Atropine
    c. Lidocaine
    d. Sodium Bicarbonate
    e. Calcium Chloride
    f. Dextrose
3. Lever Lock Cannulas
4. Alcohol Pads
5. Surgical tools
    a. Forceps-Small point
    b. Hemostat Small Curved
    c. Needle Driver
    d. Needle Driver Scissor Combo
    e. Scalpels
    f. Scissors
    g. Sutures with Needle
6. Tape, Dermicel

7. Drapes, Sterile
8. Vinyl gloves
9. Steri-Strip (skin closure)
10. IV Infusion kit
    a. IV administration sets
    b. Catheters-IV
    c. Syringe
    d. Tegaderm dressing
    e. Butterfly Needles
    f. Tourniquet
11. 4x4 gauze sponges
12. 1000 mL 0.9% NaCl IV bags (2)
13. 500 mL 0.9% NaCl IV bags (2)
14. 500 mL IV bag Dextrose (D5W) (1)
15. IV Pressure infusor
16. Stethoscope
17. Lubricant jelly
18. Foley catheters
19. Leg bag
20. Airway kit
    a. Nasopharyngeal airways (large and small)
    b. Oropharyngeal airways (5 sizes)
    c. Laryngoscope
    d. Macintosh blades (sizes 3 and 4)
    e. Laryngeal mask airway (4.0)
    f. Reinforced endotracheal tube (7.0)
    g. Stylette
    h. Syringe (20cc)
    i. Ambubag
    j. Tape
21. Non-rebreather mask
22. Manual suction device
23. Sharps Container

APPENDIX B – SIMULATOR CAPABILITIES

SimMan (Laerdal Medical AS 2009)

Airway Features

- Multiple airway skills:
  - Bag/valve mask ventilation
  - Oropharyngeal and nasopharyngeal airway placement
  - Combitube placement
  - LMA placement
  - Endotracheal tube intubation
  - Retrograde intubation
  - Fiberoptic intubation
  - LightWandintubation
  - Transtracheal jet ventilation
  - Needle cricothyrotomy
  - Surgical cricothyrotomy
  - Fiberoptic bronchoscopy
- Exhaled CO2 Flow
- Spontaneous respiration and variable respiratory rate
- Trismus, tongue edema, pharyngeal obstruction and laryngospasm
- Decreased cervical range of motion
- Decreased lung resistance
- Pneumothorax decompression at 3 sites and chest tube insertion
- Stomach decompression

Circulatory Skills and IV Drug Administration

- IV training arm with replaceable skin and veins
- Sites for subcutaneous and intramuscular injections

Pulses

- Carotid, femoral, brachial, radial, dorsalis pedis and posterior tibialis pulses
- Pulses synchronized with ECG or compressions
- Pulse strength dependent on BP selected and pulse sites

Cardiac Functions

- Extensive ECG library with rate from 20-200
- Compression artifacts on ECG during CPR

Defibrillation/Cardiac monitoring

- 3 lead (4 connectors) ECG monitoring or via the defib paddles

External Pacing – with variable pacing threshold

CPR

- ABC check
- Ventilation
- Chest compression

- ECG and heart rate can be displayed on the simulated monitor

Blood Pressure

- Can be taken automatically, auscultated or palpated
- Blood pressure arm with Korotkoff sounds synchronized with pulse for auscultation and palpation

- Easily varied BP: Systolic and diastolic can be set independently

Genitalia for Urinary Catheterization

- Male or female genitalia can be added to the simulator for urinary catheterization procedures

Sounds

- Simulator "speaking" through instructor microphone
- Heart sounds synchronized with ECG
- Independent left and right lung sounds
- Bowel sounds
- Vocal sounds, pre- or user-programmed
- Independent volume adjustment

SimMan 3G (Laerdal Medical AS 2009)

Multiple Airway Skills/Features

- Controllable open/closed airway; automatically or manually controlled
- Head tilt/Chin lift
- Jaw thrust w/articulated jaw
- Suctioning (Oral & Nasopharyngeal)
- Bag-mask ventilation
- Orotracheal intubation
- Nasotracheal intubation
- Combitube, LMA, and other airway placement
- Endotracheal tube intubation
- Retrograde intubation
- Fiberoptic intubation
- Transtracheal jet ventilation
- Needle cricothyrotomy
- Surgical cricothyrotomy
- Variable lung compliance
- Variable airway resistance
- Right main stem intubation
- Stomach distention
- Connectivity with third party respiratory simulations

Airway Complications

- Detection of proper head position
- Can't intubate/Can ventilate
- Can't intubate/Can't ventilate
- Tongue edema
- Pharyngeal swelling
- Laryngospasm
- Decreased cervical range of motion
- Trismus

Breathing Features

- Simulated spontaneous breathing
- Bilateral and unilateral chest rise and fall
- CO2 exhalation

- Normal and abnormal breath sounds
  - 5 anterior auscultation sites
  - 6 posterior auscultation sites

  Oxygen saturation and waveform

Breathing Complications

- Cyanosis
- Needle thoracentesis – bi-lateral
- Unilateral & Bilateral chest movement
- Unilateral, Bilateral & lobar breath sounds
- Chest tube insertion - bilateral

Cardiac Features

- Extensive ECG library
- Heart sounds – four anterior locations
- ECG rhythm monitoring (4 wire)
- 12 lead ECG display
- Defibrillation and cardioversion
- Pacing

Circulation Features

- BP measured manually by auscultation of Korotkoff sounds
- Carotid, femoral, brachial, radial, dorsalis pedis, popliteal and posterior tibialis pulses synchronized with ECG
- Pulse strength variable with BP
- Pulse Palpation is detected & logged

Vascular Access

- IV access (right arm)
- Intraosseous access (tibia and sternum)
- Automatic Drug Recognition System

CPR

- Compliant with 2005 Guidelines
- CPR compressions generate palpable pulses, blood pressure wave form, and ECG artefacts
- Realistic compression depth and resistance

- Detection of depth, release and frequency of compressions
- Real time feedback on quality of CPR

Eyes

- Blinking - slow, normal, fast and winks
- Open, closed and partially open
- Pupillary accommodation:
    - synchrony/asynchrony
    - normal and sluggish speed of response

Other Features

- Seizure/Fasciculation
- Bleeding
    - Simulation of bleeding at multiple sites
    - Arterial and venous
    - Vital signs automatically respond to blood loss & therapy
    - Works with various wound modules & moulage kits
- Urine output (variable)
- Foley catheterization
- Secretions
    - Eyes, Ears, Nose, Mouth
    - Blood, Mucous, CSF, etc.
- Diaphoresis
- Bowel Sounds – four quadrants
- Patient Voice
    - Pre-recorded sounds
    - Custom sounds
    - Instructor can simulate patient's voice wirelessly
- Instructor Communication
    - Multiple instructors communicate using integrated voice over IP

Pharmacology

- Automatic Drug Recognition System identifies drug & dose
- Extensive drug formulary
- Automatic or programmable physiological responses