

Simulators

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Substantial portions of the text are adapted, sometimes with minimal revision, from my chapter (DMG) on the same topic in Miller, Anesthesia, 5th Edition, Churchill Livingstone, NY, (in press). In the electronic format, those sections are designated by blue type.

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Simulation

Simulation is a powerful technique for the refinement of human performance. A medical resident verbally rehearsing his discussion of bad news with a patient, or a surgical intern tying sutures on her scrubs while on call are using simulation to improve their subsequent real-world performance. While these such simple techniques of simulation have been in use for some time, recent technological improvements have allowed for the adaptation of more advanced simulation techniques from other industries. This has opened a rapidly expanding field of highly realistic simulations of patients and entire medical environments, providing much greater fidelity and broader use than previously possible.

Simulation can be defined as the artificial replication of sufficient elements of a real-world domain to achieve a specified goal. Simulation typically refers to the replication of a broad range of an environment; replication of only a very narrowly defined sub-domain is usually referred to as a "part-task trainer." *Fidelity* refers to the accuracy with which the simulation reproduces the domain, both in the number of elements that the simulator presents, and in the faithfulness of those datastreams to their real world behavior. The fidelity required for a particular application depends on the specific goal: tying sutures on one's scrub pants may provide a realistic enough simulation for suturing a superficial laceration, but would be inadequate practice for performing a coronary artery graft anastomosis. The highest possible fidelity would be a simulation so accurate that the person in the simulator cannot distinguish it from the

real thing. Such a simulation could be said to pass the famous “*Turing test*,” posed for artificial intelligence.

Interest in medical simulation has increased dramatically as emphasis on patient safety and its relation to human performance, the work environment, and human error has become more prominent. Simulation provides critical advantages in the area of training and evaluation of personnel and for the investigation of human performance shaping factors in the medical workplace.

Simulation is most valuable when the actual behaviors to be practiced are risky, expensive, rare, and highly dynamic. Combat has been the driving force for many simulators. Good and Gravenstein point to the use of the Roman “quintain” as an early example of simulation based training¹. This device actually delivered a blow to the practicing swordsman who failed to duck correctly during hand-to-hand combat simulation. All aspects of modern warfare are widely practiced on advanced simulators by the best equipped militaries of the world today. The nuclear power, shipping, and chemical manufacturing industries have recognized the value of simulation based training and research, but no industry has embraced it as closely as commercial aviation.

Aerospace Simulation

Although a number of aircraft simulators were built between 1910 and 1927, none of them could provide the proper feel of the aircraft because they could not dynamically reproduce its behavior². Modern aviation simulators can trace their origin

to the “Link Trainer,” patented by Edward Link in 1930. This small “blue box” used pneumatics to simulate the sensation of flying an aircraft in response to the operators controls. It was widely used to train new pilots during World War II. Early aircraft simulators were used exclusively to teach novice pilots about the basics of aircraft control. Aviation simulation has steadily improved over the last 70 years with the addition of electronic controls, computer-model driven responses, and realistic graphic displays. The simulation fidelity is now high enough that commercial pilots may be certified to fly a new type of aircraft with simulator experience only. Aircraft on trans-Pacific commercial flights often carry four pilots; given work hour restrictions, the long flights and the redundancy of four pilots on the flight deck, it is not uncommon for a co-pilot to have logged more takeoffs and landings in the simulator than in the actual aircraft³.

Types of Medical Simulators

Medical simulators now in use are quite varied in their characteristics and fidelity. At the lowest fidelity (and correspondingly lowest cost) are computer assisted instruction programs that represent certain portions of the anesthesiologists work environment on-screen. Higher fidelity can be achieved by designing actual physical devices or space to replicate portions of the domain. Physical simulations can range from narrowly limited part-task trainers to full scale operating suites or intensive care units. Virtual Reality based simulation is still in its infancy, but this exciting approach uses a virtual, computer generated space with multiple sensory feedback mechanisms

to simulate the work environment of the anesthesiologist with the potential for very high fidelity, low operating costs and a broader range of datastreams than is possible with physical simulators.

Screen-Based Simulations

Screen based simulators typically use a standard personal computer (PC) to represent selected visual and auditory components of the environment, usually providing dynamic clinical data in real-time from physiologic and pharmacologic models. The predominant advantage of such a system is the widespread availability of the platform, and the low cost associated with distributing software once developed.

SLEEPER and BODY Simulation

In San Diego, Smith and associates continued a long series of work concerning the modeling of the cardiopulmonary systems and of drug distribution⁴⁻⁶. The group developed a set of linked physiologic and pharmacologic models that accurately reproduced major elements of the patient's clinical behavior. The early work had used analog and hybrid computers, more recently the systems have used standard PC's. When the models were combined with an appropriate graphical representation of the patient and clinical data on the computer screen, and a graphic user interface for the input of clinically relevant actions, the system became a complete screen-only simulator known originally as SLEEPER⁷. SLEEPER used a complex transport model to deal with gas exchange and drug distribution. This model provided the opportunity to instantiate

“drugs” with characteristics unlike those of any existing drug, as well the ability to predict the concentration of drugs in specific anatomic regions (e.g., myocardium or gray matter).

In collaboration with GE Marquette Electronics, Inc. the SLEEPER software evolved into a new program called BODY Simulation. In addition to extensions to the original transport and physiologic models an unique feature of BODY is that the monitoring equipment and anesthesia delivery equipment can be high resolution computer-screen replicas or actual GE Marquette monitors. This lends additional realism to the system as well as allowing it to be used to test the usability of the user interface of the clinical equipment. BODY is now available in a Windows NT 32-bit compatible version, for about \$1000 US (Advanced Simulation Corporation, Point Roberts, WA). The physiological and pharmacological models used in BODY are available as a Windows Dynamic Link Library (DLL), allowing custom interfaces to be built in a variety of programming environments to develop new simulation programs such as Research Triangle Institute’s Virtual Medical Trainer/Trauma Patient Simulator™.

Anesthesia Simulator™

At the University of Washington, Seattle, Howard Schwid, M.D. (formerly a research fellow with Ty Smith) and programmer Daniel O’Donnell developed a screen-based simulator originally called the Anesthesia Simulator Recorder™ (ASR™ - trademark AneSoft Corporation, Bellvue, WA)⁸⁻¹⁰. This evolved ultimately into

Anesthesia Simulator™, which is now in version 3.0. It was specifically geared to training anesthesiologists in managing patients, with more emphasis than SLEEPER (or BODY Simulation) on critical incidents and less on pharmacologic and physiologic plotting (although this is possible with AS 3.0). This system provides graphical representations of mock monitoring displays and clinical equipment, and photographs to display the patient and actions taken on the patient (See Figure 1). Interaction with this system also uses a desktop pointing device. The AS uses traditional pharmacokinetic and pharmacodynamic models drawn from the pharmacology literature to track drug levels and effects of more than 80 drugs as opposed to the physical transport models used in SLEEPER AND BODY Simulation. A unique feature of Anesthesia Simulator is that 80 cases have been contributed by nationally recognized experts. Critical events can be pre-selected by the user or selected at random by the system, and on-line expert advice is available during the case. CME and CNE credits can be arranged through the University of Washington for use of the simulator. A Critical Care Simulator has been derived from the project as well, featuring 20 ICU and ER based scenarios¹¹. The original anesthesia based program has been extended to an ACLS simulator, a critical care version, a hemodynamic simulator, and a sedation simulator, with a total of over 28,000 copies distributed.

Schwid and his collaborators conducted evaluations of the original ASR™ with 44 anesthesia residents and faculty at several teaching institutions in the United States⁹. The results showed that the ASR was easy to learn to use, was reasonably realistic, and was rated as an outstanding teaching device. The group more recently published a

study suggesting that clinicians retain ACLS guidelines better after training on the ACLS simulator than after studying the ACLS textbook for a similar period of time¹².

Virtual Reality Simulations

Virtual Reality (VR) describes a technique whereby a computer generated space and objects within it are presented to the user in a three dimensional representation with multiple sensory feedback cues. Visual data can be presented via goggles or a computer screen, and auditory information is presented via earphones. Often tactile, or “haptic” feedback is delivered to allow the realistic manipulation of objects and devices within the virtual environment. The computing power necessary is at the leading edge of available graphic workstations. The wide range of VR systems currently being developed are spread along a continuum of cost vs. realism in the input/output and modalities. VR could theoretically be used in a hybrid simulator, with a VR patient “laid over” a real clinical environment.

A complete VR patient simulator would be very complicated to produce because it requires:

- A complete computer model of the patient, the environment, and the function of every object in the environment that might be utilized (such as monitoring devices, carts, etc.).
- A means of tracking visual, audio, and touch fields of the user to determine what is to be displayed and to identify what physical actions are being performed.
- Appropriate display hardware for every sensory modality and appropriate input hardware for each action pathway (e.g. touch, speech, etc.)

- Hardware to compute all the models, conduct the tracking, and produce all the outputs to the display hardware in real time.

Virtual reality is still a developing field. There is intense interest in VR in a number of domains, particularly the military and entertainment. Although the potential of this approach is very exciting, practical VR simulators are currently quite limited in capability, are extremely expensive to produce, or in many cases, both limited and expensive. There are currently has been no publicly demonstrated VR system providing complete auditory, visual and sensory feedback with a dynamic, realistic representation of a patient and operating room environment.

Components of Comprehensive High Fidelity Simulators

The high fidelity patient simulators in use at this time have many common characteristics. Foremost is a physical representation of the patient which has multiple output modalities generated from real-time physiological and pharmacologic models. The simulators available are distinguished primarily by the characteristics of their control logic, the subset of datastreams selected for simulation, and the operator interface.

Control Logic

Early simulators required input from an operator to change states or variables represented. In essence, the physical simulator allowed the operator to manifest an internal, mental simulation. Since many physiological states can be modeled using simple algebraic formulas or differential equations that can be solved easily in real-time,

more recent simulators have sought to run continuous internal models of organ systems, normal as well as pathological, that respond automatically to inputs from the operator, the physical environment, or variables from other organ system models running in parallel.

However, not all states or changes in a patient can be modeled using differential equations. For example, ventricular fibrillation is a totally different state of heart rhythm that does not evolve continuously from normal rhythms. No model can predict exactly when a patient will suffer a myocardial infarction, or when an ischemic heart will begin to fibrillate. A model can only predict those factors that increase the likelihood of such events. Thus, most simulators incorporate other modeling techniques in addition to the basic physiologic and pharmacologic mathematical equations, including finite state models, instructor initiation of abnormal events, and even manual modulation of modeled parameters. In finite state models, different underlying clinical states are defined, each of which has appropriate entry conditions as well as transition conditions to other states. When an entry or transition condition is met, a new state becomes active which may directly trigger new observable phenomena (e.g. ventricular fibrillation), or which may alter constants in the mathematical models which then evolve in time.⁸⁻¹⁰

Datastreams

To be successful, a simulator must provide a realistic enough representation of the clinician's experience with a real patient that the subject identifies and accepts the

data being presented. Once past the acceptance threshold, the subject tends to associate that clinical cue with prior experiences with the same datastreams obtained in the real world, and tends to ignore infidelities that are otherwise readily apparent. For example, a blood pressure cuff may be placed on the arm of the simulator mannequin above an arterial line site, yet few clinicians have seemed to recall that the arterial tracing is not dampened by the inflation of the cuff. If used as a part-task trainer on pulses and blood pressure determination this would be a readily identified artifact, but when embedded in a broader simulation of the patient during surgery the variety of datastreams presented simultaneously makes such artifacts immaterial. Some datastreams are nearly obligatory, including: electrocardiogram (ECG), pulse oximetry/plethysmography, non-invasive and invasive vascular pressures, spontaneous respiration, heart and lung sounds, palpable pulses, speech, response to neuromuscular blockade monitoring, and expiration of CO₂. A wide variety of additional clinical cues are supported by the various simulators and new features are developed regularly, but nowhere in simulation is the cost-realism tradeoff so evident as in the selection and implementation of clinical datastreams.

Interface

The control logic of realistic simulators is manipulated via instructor/operator's station(s) (IOS) which allows the instructor to create or select specific patients, select and implement abnormal events and faults, and monitor the progress of the simulation session. There may also be a remote-control handheld IOS in addition to the main IOS.

The IOS typically provides logs of physiologic changes and the subject's responses and may provide graphics to support the analysis of a simulation run. Displays of data from the underlying state variables generated by the mathematical models can be used for instruction in the simulator even when these data could never be acquired in a real patient. Some screen-based simulators provide advice and tutorials linked to the management of simulated events. With realistic simulators detailed records of the simulation and the actions taken may also be made using video and audio recording of the subjects working in the simulator.

Realistic Simulators

Sim One

Sim One, the first realistic simulator for the training of anesthesiologists, was created in the late 1960's by the Sierra Engineering Company based on specifications from Abrahamson and Denson at USC¹³⁻¹⁵. The goal was to construct a simulated patient for learning the skill of endotracheal intubation, along with the induction of anesthesia. The system consisted of a patient mannequin comprising the head, neck, thorax, upper abdomen, and arms. The mannequin and the table upon which it was permanently mounted contained electromechanical and pneumatic actuators for a variety of clinical features. Appropriate to the era, Sim One did not stimulate any electronic monitors its datastreams were palpable pulses, heart sounds and movement. Sim One had a variety of electronic sensors to detect the clinicians actions. Placement of

the mask on the mannequin's face was sensed by tiny reed relays embedded in the plastic flesh of the face. A special magnetic endotracheal tube was constructed with iron molded into the plastic. Its position could be determined by magnetic sensors. Sim One could automatically recognize the identity and amount injected of four drugs: thiopental, succinylcholine, methoxamine, and ephedrine. This system depended on each drug being administered using a specific size needle, and thus it could not be expanded to identify a larger number of drugs. A standard anesthesia machine was specially instrumented to report gas flow rates (but not the concentration) of volatile anesthetic.

A mainframe computer program provided the control logic. The program would respond to drugs based on dose-time-effect curves, but there was no true modeling of pharmacokinetics or pharmacodynamics. The Sim One IOS provided readouts of the system's internal status and external outputs. Chart recordings of multiple variables could be produced. The IOS provided toggle switches or buttons to actuate a variety of preprogrammed events, including cardiac arrest, bucking, increased and decreased blood pressure or heart rate, changes in respiratory rate, and occlusion of a mainstem bronchus.

Produced in 1968, Sim One was a technological marvel, costing approximately \$100,000 (on the order of \$500,000 today) to design and build a single hand-crafted unit. It incorporated many features of today's patient simulators, and even included a number of desirable features that are not currently implemented. Sim One was used for several training purposes of which only a few involved anesthesiologists. The

investigators used the simulator to speed the training of anesthesia residents in endotracheal intubation¹⁶. Ten novice residents were randomly allocated to receive either no additional training, or to receive special training in intubation using Sim One (between 5.5 and 9.5 hours of training over a 2-week period). The investigators attempted to measure the proficiency of the 10 residents at intubation by scoring blinded copies of the residents' anesthetic records. The scoring for each record was a binary decision ("plus" or "minus") as to whether "On the basis of what you see on this chart, would you be willing to trust the anesthesiology resident in an operating room without supervision?" Performance criteria were set as (1) four consecutive plus ratings, (2) seven of eight consecutive cases with a plus rating, and (3) nine of ten consecutive cases with a plus rating. There was a statistically significant difference between the groups in the number of cases (and the number of days) to achieve the 9-out-of-10 criterion, but there was no difference in the time to achieve the other criteria. It took the simulator-trained residents 45.6 days for to reach this criterion while the control group took 77.0 days.

Although the investigators' intent was admirable, this study was seriously flawed. The simulator group received special one-on-one attention which the control group did not receive. The scoring system for the anesthetic records was poorly defined and ambiguous. The performance criteria they established were completely arbitrary. Appropriate statistical techniques were not utilized to evaluate the results. In another publication,¹⁷ the investigators stated that residents cut their number of errors in anesthesia induction by half and reduced the average time to perform an induction by

one-third after training with Sim One; however, no details of these experiments were provided. They also list other training uses including teaching nurses to perform “ventilator application” (perhaps this referred to IPPB treatments), intramuscular injection, recovery room care, and pulse and respiration measurement. They discussed the cost-effectiveness of Sim One in terms of decreased faculty time to impart specific skills, improvements in student performance, and potential reduction in patient discomfort and risk. In many ways long before their time they stated that:

“the effectiveness of simulation depends on the instructional method with which simulation is being compared. For example, if there is no alternative training method available . . . the effectiveness of a simulation device probably depends on the simple fact that the device provides some kind of learning experience as opposed to none. When a simulation device is compared with conventional on-the-ward training, however, the device's effectiveness seems related to the degree to which learning a given task is facilitated by systematic presentation of that task. Systematic presentation is not easily achieved on the wards, whereas simulation devices can provide a number of systematic patterns, such as graduation of difficulty level or complexity.”

(Credit Line: Hoffman, KI, Abrahamson, S. The ‘Cost Effectiveness’ of Sim-One, *J Med Educ*, 50:1127-28.)

The Sim One project drifted into oblivion (a planned Sim Two was never built) for a number of reasons¹⁸. It was clearly ahead of its time technologically although changes in techniques of anesthesia and of monitoring have outstripped Sim One's ability to replicate important aspects of the anesthesia work environment. Sim One was

costly and many anesthesiologists of the time viewed computers and technology with suspicion. Finally, both the investigators and the profession as a whole did not have sufficient understanding of the relevant issues of human performance for which simulator training, testing, and research would be an ideal tool. Thus, although we can now see that Sim One had great potential for teaching personnel about the management of a variety of challenging perioperative situations, its use in anesthesia then was focused primarily on standard inductions and endotracheal intubation. We now know that although simulator training in intubation can be helpful (and simulator training in complex airway management may be even more useful) most residents rapidly acquire reasonable skill at intubation through clinical experience. To be truly useful the simulator must be targeted at a different set of skills. Thus, for these, and for many other reasons lost in time, the legacy of Sim One essentially disappeared.

The Reinvention Of Patient Simulators For Anesthesiology

Several of the modern realistic patient simulators trace their roots back to the mid-1980's, when technological advances in the computer industry for the first time provided considerable computational power at reasonable cost. These simulators were developed independently of each other, and in fact, most teams had no direct knowledge of Sim One. The potential for screen based simulators in anesthesia probably followed on the development of popular screen based flight and driving simulators. Off-the-shelf waveform generators became available that gave realistic simulators the ability to stimulate electronic clinical monitors under computer control. Most

importantly perhaps, improvements in pharmaceuticals, equipment and monitoring decreased anesthetic morbidity and mortality considerably, unmasking the issues of human factors and ergonomics in the evolution of medical mishaps¹⁹⁻²³. It was these human factors that made the use of simulation technology so prevalent and visible in civil aviation, the space program, military applications, and the nuclear power industry, making its adaptation to medical use a logical progression.

A brief description of several of the realistic patient simulators in use at this time follows. The feature set of each of the simulators grows rapidly, and because of the delay inherent in publishing, the features noted for each model are likely to be incomplete. For a current description of the simulator feature sets, the reader is advised strongly to contact the manufacturers of the simulators described.

Comprehensive Anesthesia Simulation Environment (CASE)

Development

In 1986 Gaba and DeAnda began developing the Comprehensive Anesthesia Simulation Environment (CASE) series of anesthesia simulators with a primary goal of conducting research into decision making by anesthesiologists (the first transcript of an anesthesiologist responding to a simulated intraoperative crisis was obtained in Spring 1986). The architecture of the first generation CASE 1.2-1.3 simulator used commercially available clinical waveform generators to provide signals to actual clinical instruments. Other devices, such as the automated non-invasive blood pressure cuff were

“simulated” using a computer-program on a Macintosh Plus® computer acting as a virtual instrument²⁴.

The CASE 1.2-1.3 mannequin was modified to enable occlusion of the left mainstem bronchus, infusion of CO₂, and the insertion of intravenous lines. This mannequin allowed mask ventilation, intubation, and auscultation of breath sounds but did not have palpable pulses or spontaneous ventilation. The behavior of all of the waveform generators and actuators was coordinated using a central control computer. The control logic of CASE 1.2 was provided by an operator typing commands at the IOS based on a written script describing the appropriate changes for a variety of anticipated actions on the part of the subject in the simulation. An experienced anesthesiologist typically observed the activities of the subject and directed the simulator operator using a private headset intercom. This control logic and IOS enabled the simulator to respond to any actions on the part of the subject, not just those which were previously anticipated.

The CASE 1.2 system was evaluated by residents²⁴ (and later faculty and private practitioners) and was rated as very realistic, except for the plastic mannequin. The success of such a crude system which lacked physiologic and pharmacologic models lies in the exceptional variability of actual patients and in the ability of anesthesiologists to “suspend disbelief” if placed in a plausible clinical scenario. No anesthesiologist can predict the exact behavior of a specific patient in response to drugs and actions. The responses of the simulator only have to be plausible for the situation to appear very realistic. This is especially true for critical event training situations in which plausible but unusual

events are presented. On the other hand, physiologic and pharmacologic models do offer substantial advantages, including greater consistency and reproducibility of scenarios, the ability to handle multiple physiologic changes simultaneously, and greater automation of the simulation process.

In 1989 CASE 2.0 featured a major redesign which incorporated a physiologic model of the cardiovascular system²⁵. Waveforms and electronic data streams, including heart sounds, were generated directly from the cardiovascular model. CASE 2.0 was used extensively in the conduct of the Anesthesia Crisis Resource Management training program described in a subsequent section of this chapter.

Commercialization of CASE

In 1992-1993 the CAE-Link Corporation, a manufacturer of military aviation and spaceflight simulators, licensed technology from David Gaba's and Howard Schwid's group as part of its development of a commercial anesthesia simulator system. The medical simulation division of CAE-Link has subsequently evolved into Medsim-Eagle Simulation, Inc. (N.B.): One author (DMG) and his partner received a payment from CAE-Link to license their simulator technology and that author and his partner receive a small royalty on the sale of each anesthesia simulators by Medsim-Eagle. Both authors are periodically paid consultants to Medsim-Eagle Simulation, Inc. on anesthesia simulator development.)

This simulator was originally called the Virtual Anesthesiology™ Training Simulator System, but the name was later changed to the Eagle Patient Simulator™.

(Figure 2) It is completely operated by physiologic, pharmacologic, and finite state models. The Eagle Patient Simulator contains complete models of cardiovascular, pulmonary, fluid, acid-base-electrolyte, neuromuscular and thermal physiology. It includes computer-controlled electromechanical lungs with dynamically changeable compliance, embedded totally within the mannequin's thorax so that the patient mannequin can be moved onto an OR table, ICU bed, or ER gurney. The thorax can withstand full force CPR, which is automatically detected. The airway allows a variety of management techniques including mask ventilation, use of a laryngeal mask airway (LMA), oral or nasal insertion of an endotracheal tube, trans-tracheal jet ventilation (TTJV), use of a Combitube™, cricothyrotomy, fiberoptic, or retrograde wire intubation. The airway can be dynamically modified by pneumatic bladders to simulate a difficult airway or laryngeal spasm. Quantitative physical elimination of carbon dioxide through the lungs is provided so that a clinical gas analyzer can be used in its usual fashion. Other gases wash in and wash out appropriately but there is no uptake and distribution of O₂, N₂O, or volatile agents in the standard unit. The interface components are housed in a rolling cart which can be placed underneath or beside the patient bed.

The mannequin provides electronically generated heart sounds and breath sounds, dynamically changeable airway anatomy, palpable carotid and radial pulses, and a thumb twitch responding to stimulation by actual nerve stimulators. Full hemodynamic monitoring is supported, including ECG plethysmography, non-invasive blood pressure determinations, arterial and pulmonary artery pressures, pulmonary capillary wedge pressure, and thermodilution cardiac outputs. The cardiovascular

model can generate and model the hemodynamic consequences of a variety of dysrhythmias, CPR, or defibrillation. The simulator includes a cardiopulmonary bypass (CPB) model so that cardiac surgery scenarios can be presented including initiation and weaning from bypass.

Additional datastreams include eyelids that open and close, pupils that constrict or dilate in response to light, drugs or neurological injuries. Arm movements support response to painful stimuli or spontaneous movement in the awake patient. Traumatic injuries can be simulated and procedures common in trauma settings (such as placement of a chest tube) are possible, with automatic detection of thoracostomy and relief of tension pneumothorax, if present. An optional trauma module allows simulation of compartment syndrome resulting from a mid-shaft femur fracture, with displacement of the distal femur, dynamic swelling of the thigh and calf and occlusion of pedal pulses.

The IOS in the CAE Patient Simulator uses a graphical user interface (Figure 3) to provide a rich set of tools for the instructor to choose and implement different events (up to 5 events can run simultaneously), different simulated patients, and complete scenarios. The instructor can tailor each event in advance, altering features such as the onset time, severity, or manifestations of the event. Tailored events can be saved under different names, allowing the creation of an unlimited library of events or scenarios. The IOS can be controlled remotely by a simple tethered hand held LCD device, or via a battery powered tablet computer with a touchscreen interface and a cordless ethernet connection to the main IOS.

Many inputs to the device are automatic. A gas analyzer recognizes all inspired gases and passes their values to the pharmacologic models. An automated drug recognition system detects the drug and dosage administered through an electronically coded ring affixed to each syringe in conjunction with an instrumented stopcock manifold. The system can track the kinetics and dynamics of more than 90 different drugs. Using a drug editor, new drugs can be added to the library, or if desired, the kinetics or dynamics of existing drugs can be altered. The Eagle Patient Simulator also logs simulator outputs, state changes, and actions by the subject which are input to the simulator.

Medsim Eagle has demonstrated a "SmartStethoscope" system that utilizes an instrumented stethoscope to receive auditory cues transmitted from the mannequin based on automatic detection of stethoscope location. This system allows generation of a wider variety of different sound characteristics based on location, as well as higher fidelity, artifact free sound reproduction in the stethoscope.

An exciting new technology demonstrated publicly in 1999 incorporates trans-esophageal echocardiographic data via a esophageal echo probe that can be placed in the mannequin. The echo image is generated on the basis of the settings on the probe and the location and orientation of the probe tip, as determined by sensors adjacent to the esophagus. Full integration of the images to reflect the dynamic physiological models has not yet been implemented.

GAS

Gainesville Anesthesia Simulator (GAS)

Shortly after the CASE simulator was developed, a similar simulator was produced at the University of Florida, Gainesville, by a team headed by Gravenstein and Good¹. This system, called the Gainesville anesthesia simulator (GAS), also used commercially available waveform generators under the control of a central computer, along with a mannequin and real operating room equipment. GAS could stimulate non-invasive blood pressure measurement devices and provide palpable pulses. Unlike CASE, it was capable of spontaneous ventilation using a mechanical lung placed inside the operating table on which the mannequin was mounted. An interesting component of GAS was an anesthesia machine which was modified to incorporate a variety of mechanical faults that could be triggered electronically.

Over time other important features have been added to GAS, including a complex quantitatively accurate physical simulation of multiple gas exchange. The lung concentrations of O₂, N₂O, N₂, and one volatile anesthetic could be physically made to match the alveolar gas content predicted by a mathematical model of gas exchange and anesthetic uptake and distribution. Another first for GAS was a moving thumb that responds appropriately to stimulation from a nerve stimulator, based on the level of neuromuscular blockade. The Gainesville group then developed a simulator control system using physiologic and pharmacologic models.

Commercialization of GAS

The Gainesville Anesthesia Simulator was also commercialized, initially with Loral Data Systems, and later via an independent spin-off company, with Loral Data Systems as a minority shareholder, Medical Education Technologies, Inc. (METI, Sarasota, FL). The METI Human Patient Simulator™ (HPS) (Figure 4) also uses full physiologic and pharmacologic mathematical models. Its mannequin supports numerous clinical cues and interventions such as pulses, breath sounds, heart sounds, invasive airway management, etc. It provides outputs for nearly all modalities of invasive and non-invasive monitoring. Like its predecessor GAS it continues to provide quantitative physical modeling of uptake and distribution of several gases. The newest version of the Human Patient Simulator has moved the lung system to a remote interface cart, thus freeing the mannequin from its table, and allowing for full force CPR chest compressions. The HPS includes a genital/urinary system that allows user selectable urine output and Foley catheterization (the mannequin contains interchangeable genitals to provide for either patient gender), an automatic drug recognition system that uses a bar code scanner embedded in the stopcock manifold assembly (a design sketched but not implemented for CASE 3.0).

The IOS of the Human Patient Simulator runs on a PC and allows real time control of parameters and scenarios. A pen-based remote PC can be used as the IOS. The user interface primarily involves selection of files from menus and is somewhat less graphically oriented than the user interface on the Eagle Patient Simulator. This

simulator allows for graphic display of pharmacokinetic data in real-time for educational uses. .

Leiden Anesthesia Simulator

At the 1992 World Congress of Anesthesiologists, a group from Leiden, the Netherlands, led by Chopra and Bovill, unveiled the Leiden Anesthesia Simulator²⁶,²⁷. This simulator used the same architecture as CASE 1.2 and replicated many of its features as well as some of GAS. (In fact, the Leiden simulator was derived in part from technical information provided to the Leiden group by the Stanford investigators.) Like GAS, the Leiden simulator incorporated a mechanical lung capable of spontaneous ventilation. The Leiden simulator is now driven by physiological and pharmacologic models, has a new user interface, and features state-of-the-art digital lung sounds. The Leiden simulator is now operated as the "Skills Lab Anesthesiology," which will soon be charged with training every anesthesia resident in The Netherlands. There is a proposal currently under review to use the center for performance evaluation of all residents.

The SIMA Project

The Anaesthesia Simulator Sophus was developed by a group of anesthesiologists and scientists in Denmark (Herlev Hospital, Roskilde University and Risø National Laboratory). All necessary physiological parameters are animated and controlled by signals from the computer. Simulation of human response to anesthesia is

based on detailed mathematical models of pharmacokinetic/dynamic processes and the cardiovascular system. Now in Version 3, Anaesthesia Simulator Sophus does not yet appear to be quite as comprehensive as the Eagle Patient Simulator or the METI Human Patient Simulator. The SIMA project builds on the SOPHUS simulator; a collaborative group of academia and industry plans to enhance the software and hardware of Sophus and release it commercially. The Sophus simulator is also in use at the University of Basel, where it has been adapted to form the Wilhelm Tell simulator. An unique feature of Wilhelm Tell is the addition of perfused bovine or porcine organs from a slaughterhouse, upon which surgeons can perform laparoscopic procedures while anesthesiologists manage the patient.

PATSIM-1, ACCESS

A realistic simulator dubbed PATSIM-1 was developed at Stavanger College, Stavanger, Norway. While not supporting the breadth of datastreams that the commercial simulators do, it has an impressive list of features for a non-commercial simulator. It stimulates real OR or ICU monitors, has a variety of controls over ventilation parameters, and has some unique features, for example patient movement under light anesthesia. The PatSim team aspires to simulate all datastreams to interface directly with actual clinical equipment in the usual way, for example, arterial waveforms come from hydraulic pressure waves in a simulated artery on the mannequin, not an electronic waveform generator in the simulator computer. The simulator includes the unique features of regurgitation, aspiration, and peri-oral

cyanosis. It is not yet model-driven, and relies on operator inputs for simulated patient variables. ACCESS, (Anesthesia Computer Controlled Emergency Situation Simulator) a less realistic system developed at the University of Wales, is essentially a computer screen-based simulator with the addition of a mannequin. The mannequin is a standard resuscitation dummy and supports a very limited feature set. ACCESS is now in use at 10 separate hospitals in the UK.

Aftermarket Augmentation

Many simulator labs have creatively augmented the function of the commercially available patient simulators to add features of particular interest. A few examples follow.

The METI simulator has been adapted to respond physiologically to complex ventilatory parameters including the addition of PEEP, pressure support, and inverse ratio ventilation, using sensors and an external computer interfaced with the simulator via the HIDEP protocol ²⁸. Also taking advantage of the METI simulators use of the HIDEP protocol, a novel graphic display of simulator physiology has been developed that collects and organizes model driven, operator selected, and measured variables ²⁹. An ICP model was developed using the temperature, PaCO₂, PaO₂, SBP, DBP and CVP variables outputted from the Human Patient Simulator, displaying cerebral blood flow, volume, CMRO₂ and ICP in real-time ³⁰.

A Medsim Eagle simulator in use at the University of Pittsburgh has been modified to more realistically accept a laryngeal mask airway, has been fitted with

dentures that simulate dental damage during laryngoscopy, and can become diaphoretic (Personal communication, 1996, J. Schaefer, MD).

At the VA Palo Alto a reservoir of fake blood is placed in the OR table, accessible to the surgeon/actor for simulated hemorrhage; additional blood can be pumped from the control room to the reservoir to produce a virtually limitless volume of shed blood. Urine is pumped in a similar manner to the mannequin's foley catheter via a calibrated IV infusion pump; the color of the urine can be altered by addition of dye. The patient's arm has been instrumented with a system of tubes, one way valves and a source of fake arterial blood to allow arterial blood sampling and flushing of the arterial line. The Boston Simulation Center has successfully simulated a seizure using a system of piano wires attached to the mannequin's limbs. (personal communication Dan Raemer)

Uses of Realistic Simulators

Simulators can provide more than an introduction to anesthetic techniques. As in aviation, simulation is increasingly being used for education, training of personnel for catastrophic system failures, research, risk management, public relations, for evaluation and improvement of the human-machine interface, for assessment of operator performance, and for investigation of accidents. There is an enormous breadth of simulation activities worldwide, and new and more imaginative uses are continuously being developed. The simulator is an excellent tool for a diverse set of applications, and is adapted to fit the needs of the local environment and users.

Education and Training

For our purposes, we draw a distinction between *education*, which involves teaching conceptual knowledge, and *training*, which involves teaching specific skills. Using the simulator as a tool to assist in imparting principles of physiology and pharmacology is *education*; using the simulator in its highest fidelity mode in concert with a realistic clinical environment to learn or practice clinical skills and behaviors is *training*.

Simulators have been used for community outreach programs, exposing high school aged students to medicine as a potential career path.³¹ A common educational use of simulators is for introduction to anesthesia principles for medical students and starting anesthesia residents. Courses can be adapted to any level: most simulators can be configured with as little or as much complexity as desired. Undergraduate and pre-clinical medical students can learn about pharmacology, physiology, physical examination skills and monitoring experientially in the simulator. During their anesthesia or ICU rotations they can discuss cardiovascular physiology and experiment on the simulator at the same time^{32, 33}. Andrew Lee succinctly states the benefits of simulator-based medical student teaching programs:³³

- The ability to bring clinical applicability to the early medical students
- The ability to teach topics that are difficult to teach in a purely didactic form

- The provision of a natural bridge between didactic and clinical work that is safe
- An introduction to our specialty and our department early in a student's career
- An ability to provide a service that increases our standing in the local and national medical community.

Training

Clinical medical or nursing students can learn procedural skills, get a chance to manage an unstable patient on their own, and learn to handle dynamic situations using a simulator. However, most training applications are targeted at the post-graduate clinician for whom more intensive and more advanced training is appropriate.

ACRM

While analogies between aviation and anesthesia have been widely used, it has only been a decade since the medical community has begun to take serious notice of the striking similarities between the work environment in dynamic medical domains and in industries like aviation. These domains are similar because they share the cognitive profile of intense time pressure, high risk, continually shifting and competing goals, and complex human-machine interactions.

An analysis of the evolution of critical events in the early simulator prototype suggested gaps in the training of anesthesiologists concerning several aspects of

decision making and crisis management which were not systematically taught during standard residency.^{21, 22, 24, 34-37}

Cockpit (now Crew) Resource Management (CRM), a system of training aircrews to perform effectively during crises, was first adapted to medicine in between 1988 and 1990 when, armed with their new realistic simulator, David Gaba, Steve Howard and Kevin Fish began teaching these concepts at the VA Palo Alto and Stanford University³⁸. The course, termed Anesthesia Crisis Resource Management (ACRM), deals with technical aspects of managing critical events, but more importantly, addresses the behavioral skills that correlate with effective performance. These skills cannot otherwise be practiced, and cannot be learned by osmosis; they often are contrary to the individualistic “unassuming” work style of many anesthesiologists. Anesthesiologists, often used to working alone, must learn to work effectively as a crew with other anesthesia providers and as a team working with other crews such as nurses and surgeons.

The ACRM course, as taught at VA/Stanford begins with a didactic introduction to CRM principles, team building exercises, practice at accident analysis of trigger videos using the principles of CRM. Most of the one day course is then spent alternating highly realistic simulations of critical incidents with detailed videotape debriefings. The realistic simulations make use of trained actors who play the roles of surgeons, nurses, and other personnel. Participants get the opportunity to be in the “hotseat,” as well as be a “first responder,” who remains blinded to the scenario, but may be allowed to be summoned as help by the hotseat trainee. The course syllabus eventually evolved into a

textbook³⁹, which has been translated into four languages. Key points applied throughout the course include:

- Allocate attention wisely: manage distractions and competing tasks
- Use all available information: check additional datastreams to filter out artifact
- Avoid fixation errors: re-evaluate often
- Distribute the workload: work as a manager as much as possible
- Utilize all available resources: be creative
- Communicate effectively
- Resolve conflicts quickly: concentrate on what is right rather than who is right

Since the inception of this course in 1990 the response has been quite positive: the ACRM curriculum has been formally adopted as a major focus of training at several major teaching institutions – Boston Center for Medical Simulation; Canadian Simulation Centre (Toronto); University of Pittsburgh, University of Alberta (Edmonton), Washington University, (St. Louis); Southern Health Care Network (Melbourne, Australia) Royal Perth Hospital (Perth, Australia). Several variant curricula similar to ACRM were developed based on the textbook and based on first-hand observation of early ACRM training courses at the VA/Stanford center. These variants include the Rational Anesthesia curriculum in Denmark (which has been given to the majority of Danish anesthesiologists and anesthetic nurses), and simulation training courses in Brussels, Belgium.

ACRM training is mandatory for anesthesia trainees at our institution. The curriculum is fully staged through the residency, a completely different ACRM II and

ACRM III course are given to second and third year anesthesia residents respectively. The advanced courses emphasize increasing safety culture in the operating room for residents soon to graduate on to the practice of anesthesia, and to increase their use of ACRM concepts as they debrief their peers and themselves after real-life critical incidents.

The ACRM III course features a unique scenario in which the patient is allowed to die. This complication is absolutely avoided in the basic courses because it carries with it a profound emotional effect on the participant that interferes with effective debriefing. In ACRM III, it is exactly those issues with which we deal: how to recover from a disastrous outcome, how to notify and recruit help from the correct hospital personnel, how to impound the OR if an equipment related problem is suspected. After the anesthesiologist, in conjunction with the surgeon decide to suspend their resuscitation efforts, the trainee is led by the surgeon to a waiting area where an actor plays the role of a family member, and the trainee gets the opportunity to practice delivering bad news. The OR scenario and subsequent family conference are videotaped for detailed debriefing. Residents' comments on this activity have been very positive remarking on the fact that training in this difficult aspect of practice has rarely been offered. An analysis is currently underway on the trainee's performance during the family conference.

ACRM training is very complex, and requires skills and considerations that are unique. For that reason, special training for ACRM instructors has been developed by The Working Group on Crisis Management Training in Health Care (comprised of the

three pioneering centers in the development of ACRM – VA/Stanford Simulation Center, the Boston Center for Medical Simulation and the Canadian Simulation Centre). This Working Group has developed and tested a three day ACRM Instructor Training Course and has produced a 150 page training manual for ACRM Instructor candidates. Experience with the instructor training course suggests that the most difficult aspect of ACRM instructing is “debriefing”, and that new instructors will require a significant period of experience, preferably under supervision by more senior instructors, before being ready to be a fully independent ACRM instructor. ACRM instructor training continues at these three Centers under the auspices of The Working Group.

The concepts of ACRM apply to many healthcare environments outside the operating room, and many investigators have been actively working to extend it to: radiology^{40, 41}, in hospital resuscitation “code” teams⁴², and OR teams including surgeons and nurses⁴³. Lou Halamek, a neonatologist at Stanford University has developed a CRM course to train pediatricians and neonatal ICU nurses for delivery room and NICU crises. The course can be adapted to provide a measure of combined team training, incorporating obstetricians and anesthesiologists^{44, 45}.

TOMS

Team Oriented Medical Simulation is another curriculum whose roots are in aviation and CRM. It was developed independently of ACRM, by Hans Gerhard Schaefer and Robert Helmreich⁴⁶. It has many characteristics in common with ACRM, but includes more emphasis on the social psychology of team interactions in the

operating room and is always conducted with true combined teams of anesthesiologists, surgeons, nurses, and ancillary personnel. Communication skills between crews are heavily emphasized.

What are the advantages, disadvantages and obstacles of attempting combined team training? The advantages clearly include:

- The ability to foster team interaction
- Cross-training (or at least cross discipline understanding) of personnel
- Exploration of actual team interactions rather than scripted interactions
- Training the teams as teams rather than the individuals to work in teams

On the other hand, disadvantages and obstacles include:

- The political difficulties of bringing all crews on-board simultaneously for combined training
- The expense and political difficulties of withdrawing an entire team from actual patient care for training
- Current lack of highly realistic work for surgeons to perform. The Wilhelm Tell simulations can encompass only a few surgical procedures, and thereby excludes many surgical specialties.
- Inability to cover technical and cognitive issues fully for each crew
- Inability to present a full spectrum of teamwork challenges

We foresee that eventually both approaches will be utilized. ACRM-like approaches allow focused training for specific disciplines about cognitive issues of resource management and specific teamwork issues pertaining to that discipline while allowing for discussion of relevant technical matters. Combined team training, like TOMS, would then provide a supplementary training experience specifically focused on interdisciplinary teamwork issues.

Other Examples of Simulation Based Training

The ASA Difficult Airway Algorithm provides a cognitive framework for managing one of the most challenging clinical scenarios. However, performing procedures from memory for the first time under intense time pressure on a desaturating patient is not optimal. Skills that are used rarely, but expected to be performed rapidly and flawlessly must be practiced. The simulator provides a perfect setting: a realistic airway, the necessary equipment, and a fully realistic environment for practicing those skills. A study of 18 anesthesiology residents before and after a simulation based difficult airway course showed a significant improvement in performance, based on the clinical outcome predicted by the simulator models, (i.e. whether or not the simulated patient died of hypoxia)⁴⁷. There was a high degree of acceptance of the course, and 93% of residents felt the training would improve subsequent performance. There was, however, no control group given a lecture, book, or traditional mannequin based course for comparison.

In concert with the FDA Glaxo Wellcome Pharmaceuticals decided to provide extensive training to clinicians on the new opiate remifentanil as a part of its introduction for clinical use. Real-time clinical simulation was an ideal training forum for that training because:

- Remifentanil has unusual kinetics, which many simulators can illustrate effectively using model driven real-time plots simultaneously with clinical cues.
- Total intravenous anesthesia (TIVA) is a technique requiring different skills and considerations than inhalation anesthesia, and requires familiarity with new and potentially unfamiliar equipment and principles that can be practiced in the simulator prior to use.
- Safety measures geared toward ensuring ventilation of the patient also help ensure anesthetic delivery; TIVA removes some or all of that tight linkage, and thus has a different set of safety considerations that necessitates careful consideration and training.

Several curricula were developed using simulators to train clinicians to use remifentanil safely. W. Bosseau Murray reported on perhaps the largest of these programs⁴⁸ and found a very high degree of simulator acceptance among the participants, who were mostly (79.9%) new to patient simulation. There was a significant increase in participants comfort level in using the drug, and all of the participants rated the simulator as an “excellent” or “good” means to learn about new agents such as remifentanil.

Several simulation centers conduct training for personnel from companies that produce and sell pharmaceuticals and medical devices . The University of Florida, Gainesville has run such courses for many years, and the course at the Boston Center for Medical Simulation has the engaging title of “Anesthesia for Amateurs.” These curricula allow sales representatives and executives to achieve a better first-hand understanding of the challenges of the clinical environments in which their products are used.

Research

The realistic simulator is an excellent laboratory for the study of human performance and performance shaping factors, for investigations into the cognition of clinical decision making, and for evaluation of equipment and the human-machine interface.

(Table 1)

Study of Critical Incidents in Anesthesia

In 1989 Gaba and Deanda published the first of a series of papers on the response of anesthesiology trainees, faculty, and private practitioners to critical incidents using a realistic simulator. Using incidents that varied in type and severity, they measured the latency to detection and correction of the event. The subjects were asked to “think aloud” to gather information about their detection and management strategies.

For each incident there was considerable inter-individual variability in detection and correction times, in information sources used, and in the actions taken. In each experience group there were “outliers” who required excessive time to solve the

problem or never solved it. In each experience group at least one individual made major errors which could have had a substantial negative impact on a patient's clinical outcome. For example, one faculty never used electric countershock to treat ventricular fibrillation. One private practitioner treated an endobronchial intubation as if it was "bronchospasm" and never assessed the symmetry of ventilation. One resident never found an airway disconnection.

The average performance of the anesthetists tended to improve with experience, although this varied by incident. The performance of the experienced groups was not definitively better than that of the second year residents (who were in their final year of training at that time). Many (but not all) novice residents performed indistinguishably from more experienced subjects. The elements of suboptimal performance were both technical (choosing defibrillation energies appropriate for internal paddles when using external paddles; ampule swap; failure to inflate the endotracheal tube cuff resulting in a leak) and cognitive (failure to allocate attention to the most critical problems, fixation errors).

Schwid et. al. from the University of Washington used the screen based "Anesthesia Simulator Consultant™" to perform a similar experiment⁴⁹. This technique in some ways allowed a more detailed analysis of the subjects actions, but suffered from using the screen based OR environment. Like Gaba and Deanda, they found major errors and omissions in all experience levels, in both event detection and treatment. Fixation errors were noted, and subjects failed to make operational knowledge they had about diagnosis and treatment of specific problems. For example, 60% of subjects did

not make the diagnosis of anaphylaxis when confronted with heart rate, blood pressure, peak inspiratory pressure, and skin rash data.

Botney et al.^{50, 51} analyzed videotapes from 18 different simulator training sessions on crisis management. In one event a volatile anesthetic vaporizer had been left on at 4 percent and was hidden beneath a printout from the NIBP. Simultaneously there was a mechanical failure of the capnograph, making it impossible to confirm endotracheal intubation using CO₂ measurements. This event purposefully presented an invitation to become fixated on the endotracheal tube while ignoring other relevant information. Five of 18 subjects never discovered the volatile anesthetic overdose despite catastrophic effects on blood pressure and heart rate and clear evidence that the endotracheal tube was correctly placed. Of those who did detect the vaporizer setting the average time to detection was nearly 4 minutes, with some subjects taking more than 12 minutes.

In the second event studied there was a loss of pipeline oxygen supply while an anesthetist was assuming the care of a critically ill patient who required a FiO₂ of 100 percent to achieve satisfactory blood oxygenation. The oxygen cylinder on the machine was empty (i.e., it had not been checked by the initial anesthetist who left the case after becoming ill). The pipeline failure was quickly detected (19 seconds), but the responses to it were extremely variable and showed a variety of problems. Five of 18 closed the anesthesia circuit (which preserves the existing O₂ in the circuit) but all 5 subsequently switched to ventilation with a self-inflating bag using room air or to mouth-to-tube ventilation. Five of 18 could not open the reserve O₂ cylinder because they could not

locate the tank wrench attached to the machine (it tended to rest between two gas cylinders). Several teams had trouble in mounting a new tank on the anesthesia machine; problems with the gasket disk were frequent. The individuals did not appear to have a well-formulated plan for managing this event and they did not optimally coordinate their actions with their assistants or with the other OR personnel.

Devitt, et al.⁵² studied the response of anesthesia residents and faculty to 5 matched pairs of simulated intraoperative events embedded in two scenarios. They evaluated response on a 3 point scale (described in more detail in the section below on performance assessment). Although faculty scored higher than residents overall, they scored lower on two events: “sinus bradycardia during peritoneal traction,” and “coronary ischemia.” In both cases residents executed a “corrective treatment” more frequently than did the faculty. These two and several other events showed low “internal consistency” in this study (the rank order pattern of response across subjects for these events did not match that of the other events); however, the lower performance of faculty on two events of apparent clinical importance was unexplained. Were faculty less likely to execute a corrective action in these events because they were more willing to assess the situation over time or because they were less vigilant or less decisive? This study did not answer these troubling questions.

Performance and Ventilation Related Events

The performance of clinicians using standard monitors and displays during simulated critical ventilation related events was investigated using a realistic simulator.

Latency to diagnosis, means of diagnosis, and latency to treatment were recorded. Following the simulations, subjects were interviewed for meta-cognitive information. In general, subjects made incomplete use of crucial datastreams in monitoring and diagnosing ventilation related problems. Poor instrument design was implicated as a contributing cause⁵³⁻⁵⁵.

Simulation technology can be used to investigate the utility of monitors or techniques that would be impossible to validate in the real world due to the infrequent and unpredictable nature of certain types of incidents, and the ethical issue of withholding techniques from the control group that are thought to increase patient safety. For example, Lampotang et. al.⁵⁶ were able to demonstrate a reduction in the time to diagnosis of a ventilation related critical incident in a group randomized to utilize oximetry and capnography in the simulator, as compared to a control group going through otherwise identical simulations without those monitoring modalities.

Workload & Performance

Byrne et al.⁵⁷ reports on the use of charting accuracy during critical incidents in a moderate fidelity simulator as a fully embedded secondary probe, using this measure of spare capacity as a proxy for performance. The study has been criticized⁵⁸ because of the authors assumptions about the relationship between the primary task (taking care of the patient), the secondary task (charting fidelity), and “performance”. A good performance on the secondary task does not necessarily ensure a good performance with respect to the patient, in fact, one might argue that an effective strategy for good

“performance” would be to sacrifice charting accuracy temporarily to concentrate on managing a critical incident! Further, the relatively low fidelity of the simulations (no surgeons or nurses, the presence of a friendly “tutor” who was an investigator, the unusual chart presented to the subjects (2.5 minute time intervals) and the short duration of the simulations (three critical incidents in 25 minutes) make these findings wrought with artifact.

Performance Shaping Factors

In the most comprehensive simulation based experiment performed to date by the VA Palo Alto/Stanford group, the performance of anesthesia residents was measured under two carefully controlled and highly disparate conditions: acutely fatigued and sleep extended. In the fatigued condition, subjects were kept awake and busy with anesthesia related tasks for 24 hours prior to the simulated cases; in the sleep extended condition subjects were required to extend their sleep each morning by at least two hours for four days prior to the case. Subjects kept a sleep log, wore a wrist activity monitor, and wore ambulatory EEG devices during the sleep deprivation phase and the simulated cases.

Performance measures were in 3 categories: pure laboratory tests of vigilance (the psychomotor vigilance task, PVT), fully embedded and partially embedded secondary probes; and full clinical patient care (of a simulated patient). Subjects had to conduct a complete anesthetic (duration approximately 4 hours) including preoperative assessment, pre-use checkout of key equipment and induction and maintenance of

anesthesia. During the assessment and machine checkout as well as the case, the investigators embedded a variety of technical and clinical faults that had to be recognized and handled appropriately.

The key findings of these studies can be summarized as follows:

- Sensitive laboratory tests of psychomotor vigilance detected large decrements reaction time in the fatigued state vs. the sleep-extended state. The decrement was greatest early in the morning following sleep deprivation.⁵⁹
- Performance of the pre-anesthetic equipment checkout was very poor in both groups of residents, no difference between groups was detected.⁶⁰
- Most subjects preserved performance⁶¹ and vigilance while acutely sleep-deprived during care of the simulated patient, but there were subtle indicators of impairment during the fatigued state. When fatigued, subjects seem to focus their attention on patient monitoring and reduce their other activities.
- Some subjects had a high incidence of microsleeps in the sleep-deprived state⁶². A few subjects (approximately 16%) had significant periods (minutes) of profound complete sleep during the care of the simulated patient. During these periods vigilance and performance can be assumed to be zero. In the few instances when a clinical probe or vigilance probe coincided with such a sleep period, the measured performance was in fact zero. Interestingly, this did not result in catastrophe to the simulated patient, for several reasons:

1) During the maintenance phase of anesthesia during straightforward surgery in healthy patients acute changes are possible, but uncommon. Thus, it is possible to fall asleep for several minutes or longer and have nothing untoward occur in the interim.

2) Our clinical vigilance probes "timed out" after 3 minutes if not detected.

Furthermore, the vital signs "ramp" probes leveled out at abnormal, but non-catastrophic values. Had the vital signs continued to change without detection a clinical catastrophe would have eventually occurred.

3) We had few clinical events. By chance only one occurred while a subject slept and several events were missed by non-sleeping subjects and by sleep-extended subjects.

- Clinical performance varied strongly between individuals and within individuals over time. The subjects in the sleep-extended state made a surprising number of errors in detecting or acting upon abnormalities and in responding to vigilance probes. Clearly, sleep deprivation and fatigue are not the only factors responsible for sub-optimal performance.

Other Research Uses

The realistic simulator has been used to evaluate a new equipment checkout regimen⁶³ and to compare the performance of clinicians with an artificial intelligence system for post-operative cardiac surgery⁶⁴.

Other ongoing investigations the authors are aware of include:

- Holter monitoring of clinicians during simulated critical events^{65, 66,}
- Analysis of teamwork and the effects of demeanor on communication and team performance,
- Use of a head-mounted camera to study dynamic decision making in OR personnel during realistic simulations of critical incidents.

Ancillary Uses Of Simulation?

Clearly, education, training, and research comprise the major applications of patient simulation, but there have been a number of other interesting uses. The simulation center has been used as a “film studio” to create realistic clinical vignettes for films (e.g. three in the ASA Patient Safety Videotape series) and for medicolegal defense. The simulator has been used for pre-procurement testing of clinical equipment (including new devices which could not be evaluated in clinical use because they did not yet have FDA approval), and as part of the training of clinicians to use new equipment. Similarly, simulators have been used by manufacturers to test the usability of prototype devices.

Effectiveness

The most important question concerning simulator-based training in anesthesiology is its cost-effectiveness. This is a complicated question that has two relatively independent components. The first component is: What is the impact and benefit of the training on the performance abilities of participants? The second component

is: What does it cost to achieve that impact? In principle, simulation has many advantages as a training tool ²⁴:

- There is no risk to a patient
- Exercises in routine procedures can be repeated intensively, while scenarios and events involving uncommon but serious problems can be presented at will
- Participants can learn to use actual complex devices (with a hands-on simulator)
- The same scenario can be presented independently to multiple subjects for evaluating individual or group performance
- Errors can be allowed to occur which in a clinical setting would require immediate intervention by a supervisor
- The simulation can be frozen to allow discussion of the situation and its management, and it can be restarted or begun anew to demonstrate alternative techniques
- Recording, replay, and critique of performance are facilitated, since there are no issues of patient safety or confidentiality.

The fidelity required of the simulator and thus the choice between screen-only and realistic simulators is dependent on the intended goals of the training and the relevant target population. A spectrum of computer-based training is possible and is in use at many institutions. Computer-assisted instruction programs and part-task trainers are used to teach basic concepts and technical material, such as the uptake and distribution of inhaled anesthetics or pharmacokinetics of intravenous drugs. These will be appropriate for students, novices, and advanced residents, and experienced practitioners. Screen-only simulators are inexpensive and easy to use. They allow the

presentation of and practice with the concepts and procedures involved in managing normal and abnormal case situations. They too will be useful for a large number of user populations. Realistic simulators can be used to capture the full complexity of the real task domain including the human-machine interactions and the complications of working with multiple personnel. Although they can do “double duty” in roles where less sophisticated simulators might suffice, their strength will be in the training of residents and experienced practitioners in a variety of domains. Regardless of the device used, the simulator is only a teaching tool which must be coupled with an effective curriculum for its use.

The evaluations conducted so far suggest that a variety of simulator-based training curricula are powerful techniques that students as well as both novice and experienced anesthetists believe to be highly beneficial to their education and training. Questionnaires⁶⁷⁻⁶⁹ and structured interviews⁷⁰ have documented that participants and instructors alike believe that simulation training has improved the participants clinical skills. One clinician⁷¹ ascribed her success in managing a cardiac arrest on an airline flight to skills learned during ACRM!

Good et al.⁷² reported on a randomized study of the effect of simulator-based training on novice resident performance. Twenty-six beginning residents, matched for previous training and gender, were randomized to receive either daily simulator training sessions or daily lectures on 10 predefined learning objectives during weeks 2 and 3 of the residency. Resident performance was assessed both by a written test and by

evaluations of clinical ability by supervisors at week 1, 3, 8, and 13 of training. There was no difference in performance on the written test. While there was a trend of improvement in the overall raw clinical ability scores for the simulator group at weeks 3 and 8, this was not statistically significant. However, the change in clinical score was significantly greater for the simulator group than for the lecture group at weeks 3 and 8, but not at week 13, by which time the change in clinical score was identical for the two groups. This study suggests that there may have been somewhat faster improvement in clinical ability when simulator-based training was used, but that by 3 months of anesthesia experience all residents had improved their ability by the same amount. It was noted that additional work is needed to refine and coordinate the clinical and simulator curricula and also that continuing simulator exercises may have benefits over the single “bolus” of training over 2 weeks.

As the developers of Sim One pointed out, when simulation provides an opportunity to teach material that cannot be taught in another way, as for the systematic instruction of anesthesiologists in handling severe critical events such as cardiac arrest, anaphylaxis, or malignant hyperthermia, there is nothing with which to compare the simulator.

Assessing whether the actual outcome of patients can be affected by this, or any other training modality will be extremely difficult and expensive. Those investigating simulator-based training do not believe that such an outcome study is logistically feasible.³⁶ Determining the impact of a given type of simulator training on the intermediate variables of “performance” and “ability” is feasible, but will not be easy.

The Leiden group has provided data supporting the contention that simulation training improves performance on handling a malignant hyperthermia situation. However, there is a potential for substantial bias when attempting to measure the impact of the simulator training by using performance in the simulator as a criterion. The control procedures as used by the Leiden group alleviate this bias but cannot eliminate it⁷³.

Perhaps of even greater importance there is currently no gold standard methodology for measuring the clinical performance of anesthetists in actual practice. Ironically, the simulator itself provides a tool for presenting the same calibrated scenario to multiple anesthetists and may thus be a crucial in developing such performance measures. The work to date on performance assessment using simulation is encouraging in that the measures already tried appear to be as good or better than those already used by the profession for credentialing and peer-review. However, it may be necessary to further validate the performance assessment tools. Definitive studies of these tools and of the impact of various training curricula can be designed, but they will be very costly due to the high inter-individual variability (requiring a large number of subjects) and the complexity both of conducting realistic simulation scenarios and of conducting fair and thorough objective and subjective performance assessments. There is now in place a large enough network of simulation centers to support such a definitive multi-center study, but it is uncertain whether any funding agency will be willing to support the costs of this complex study.

Other factors complicate the assessment of the effectiveness of simulator-based training. Studying the impact of a single session of a course which uses a new

technology and a new approach to training may underestimate the course's impact were it to be used on a regular and repetitive basis. For example, it is widely believed in commercial aviation that CRM training must begin with the initial training of pilots and be continued throughout their career. Social psychologists Robert Helmreich and H. Clayton Foushee, two of the main architects of CRM training, have written: "Data indicate that even intensive initial CRM training constitutes only an awareness phase and introduction to the concepts, and that continuing reinforcement is essential to produce long-term changes in human factors practice⁷⁴." Similarly, United Airlines states in their CRM manual: "Command/Leadership/Resource management {United's terminology for CRM} cannot be a one-shot approach. It has to be a coordinated long range program. It must therefore be an integral part of the entire training effort: new hire training, transition and upgrade programs, and recurrent training.⁷⁵" These experiences lead to a conundrum. If they are true it makes no sense to delay a decision to implement a long-term program of this type of training while awaiting definitive proof of its effectiveness, since that proof can only come from very long-term evaluations after the training is fully deployed. The decision to implement such long-term programs, whether in aviation or in health care, must be made largely on the basis of face validity and imperfect empirical data.

Finally, simulation training must be viewed within the context of an integration of educational and training experiences. Though the simulator offers important opportunities to target training situations that cannot be safely presented any other way, real-world experience has a much larger cumulative impact. The same principles

and procedures taught in training must be reinforced within the real-world operational environment. Simulator-based safety training can be totally negated if production pressures or latent failures in the workplace create disincentives to implement its teachings effectively. In such settings it could appear that simulation training is failing to yield higher patient safety when in reality it is other factors that are simultaneously eroding safety. Any long-term studies of the impact of simulation training will need to control for this potent confounding variable.

Costs of Patient Simulation

A key question concerning the use of simulators is the costs of simulator-based training? These costs depend on many of the same factors that determine the curriculum to be used:

- Types of training involved, ranging from technology in-service to training in basic anesthesia skills, critical incidents management or crisis resource management
- Target populations for the training, whether equipment technicians, medical students, novice residents, experienced residents, nurse anesthetists, teaching faculty, or private practitioners
- Organizational and financial characteristics of the institution

The hardware and software cost of the screen-only simulator is quite low (as low as \$1,500), while the equivalent cost of a complete hands-on simulator is relatively high. The prices of commercial simulators can be over \$200,000 depending on features - contact the manufacturers for detailed information- and this does not include the

necessary clinical and ancillary equipment and space. However, even these large expenditures do not dominate in the cost equation since the capital equipment and space renovation can be amortized over a relatively long useful life, with appropriate provisions for service and upgrades⁷⁶. The dominant cost to any department using the simulator is likely to be that of providing expert instructors and of contributing to the professional direction of the simulation center. While a credible expert must oversee the curriculum and the operation of the center, the type of training and the target population will determine the actual amount of expert instruction that is required per participant. For example, a single faculty member can review the summaries of exercises performed by residents on a screen-only simulator in a few hours per resident per year. A single instructor can use the simulator to demonstrate pulmonary or cardiovascular physiology to a whole class of medical students. When training novice residents in basic anesthesia skills it might be possible to have senior residents or fellows conduct the sessions at a low marginal cost or to use faculty in one-two hour blocks without requiring extensive additional expenditures. However, when training experienced residents and practitioners in complex material, such as the handling of critical events, there is likely to be no substitute for expert instructors. The cost of expert instruction will depend on the organizational arrangements of the institution which vary widely.

Another organizational factor which affects the cost has to do with making trainees available for what can be complex, exhausting, and lengthy training sessions. Removing residents from revenue-producing work for training purposes is expensive.

On the other hand, if simulator training could allow residents or other anesthetists to work more safely and more efficiently, the benefit could outweigh the cost.

Furthermore, many programs have used simulation training as a recruiting tool, both to attract students into anesthesiology, and to attract the best candidates to a specific residency . In the long run, if simulator-based training is found to be desirable, innovative changes in organization will evolve to allow it to occur.

Simulation Centers

Although one can install a simulator in a laboratory or conference room many institutions have equipped complete simulation centers. Typically these centers provide a separate control room to allow complex simulations to be presented without an instructor intruding on the simulated case. The center also provides a debriefing room where videotapes of the simulation session can be reviewed. Some centers have elaborate computer controlled audio-video systems allowing the recording of multiple views with real-time annotation of the tapes and rapid search to marked portions of the tape. Dedicated centers facilitate all types of research and training applications of simulators but are especially important for intensive activities such as ACRM. Typically a technician, anesthesia fellow, or administrator manages the Center, coordinating scheduling, logistics, as well as assisting the experienced clinicians conduct training and research.

The costs of a simulator training program can be shared between the anesthesia departments of multiple institutions and even more frequently now the cost is shared

between departments within a single institution since the simulator is a resource tool for training in other areas besides anesthesia. The patient simulator has proven to be a suitable platform for training of physicians, nurses, technicians, and other medical and technical personnel, both in homogeneous groups and in combined teams.

At this time, despite the lack of definitive cost-effectiveness data, training with realistic simulators is under way in at well over 100 sites around the world, with many of them choosing to conduct fairly “high-end” crisis management and critical incident training sessions. These programs have already “voted with their feet” on the issue of cost versus benefit, judging that the many varied opportunities afforded by patient simulation outweigh the initial and recurring costs. With so many centers exploring the realities of simulation training we can expect to see additional data on efficacy and cost within the next few years, although definitive studies may never be available.

Performance Assessment

Several research groups have been investigating performance assessment tools for use during simulation sessions. The most common assessment is to evaluate the quality of the technical management of the situation presented, that is what clinical actions were taken in response to an abnormality. Simulation offers some benefits in assessing technical performance. Because the nature and cause of the critical incident is known, one can, in advance, construct a list of essential or appropriate technical activities with relative weights of importance. For example, in assessing technical performance in managing malignant hyperthermia (MH), terminating the trigger agent

and administering IV dantrolene would be critically important, even essential, items while cooling measures, hyperventilation, and bicarbonate therapy would be among many appropriate (but less critical) technical responses. One can also predict in advance specific technical pitfalls to look for. For MH these might include diluting dantrolene with the wrong diluent (not sterile water) or insufficient quantity of diluent. These are pitfalls known to plague those unfamiliar with MH therapy.

Technical Assessment

Chopra, et al assessed technical performance in simulations of MH and anaphylaxis for anesthesiologists using a checklist of appropriate actions⁷³. However, they used only a single rater and could not measure the variability between raters.

The University of Toronto (Canadian Simulation Centre) has demonstrated good interrater reliability ($\kappa = 0.96$) between 2 raters of a very basic performance assessment rating system using a simple three point scale of the response of an anesthesiologist work alone to a simulated clinical anomaly: 0= no response; 1= compensating intervention; 2 = definitive management.⁷⁷ They produced scripted test tapes in which an anesthesiologist-actor responded at each of the three predetermined levels of performance to 10 different clinical problems ranging in difficulty from very simple (bradycardia during peritoneal traction) to very difficult (anaphylaxis). This strong interrater reliability must be interpreted with caution. The scenarios were acted out to demonstrate clearly different levels of performance, consistently over the

duration of each clinical problem. Further, raters might have discerned that each problem was portrayed exactly once at each performance level.

A subsequent analysis of the rating system showed that there was poor internal consistency between the different anesthetic problems presented in the scenarios⁵². This suggests that the items acted “independently, reflecting different aspects of anesthesia care.” When aggregated across the five problems the results were affected by the “level of importance placed on each problem by individual subjects⁵².” However, the same group has shown that a slightly modified simulator test can discriminate between several broad practice categories⁷⁸ both in terms of the score on the three level scale and in rapidity of response⁷⁹. This group also showed that a six-event simulator test yielded good interrater reliability and good correlation between clinical evaluations, written tests of knowledge, and simulation performance for fourth year medical students⁸⁰.

Kurrek’s group subsequently compared scores from raters viewing live performances in the simulator with performances viewed on videotape, and found good interrater reliability, with the weighted kappa statistic not significantly different at $p < .05$. This study again used a relatively simplistic three level rating scale⁸¹.

The VA/Stanford group assessed technical performance in 14 anesthesia teams, each managing two different complex critical events (MH and Cardiac Arrest)⁸². Scoring was based on a pre-defined checklist of appropriate medical/technical actions for recognition, diagnosis, and therapy. Point values for successful implementation of

each action were assigned subjectively by the investigators in advance. Some items were rated as “essential items” whose absence resulted in a net score of zero points. Raters recorded the presence or absence of each action during a scenario and then summed the point values for all actions recorded as present. Each technical score was expressed as the fraction of the maximum possible score (100 for Cardiac Arrest, 95 for MH)

In this study⁸², three raters agreed frequently concerning the presence or absence of checklist items, and the interrater variability was good (approximately 0.6). The teams scored well technically, usually accruing over 80% of the available points, and never missing an essential item. This should not be surprising since a) participants had at least two years of post-graduate medical training and all had previously received ACLS certification, b) the scenarios portrayed in this study have well-known treatment protocols and the most critical items could be accomplished by only one or two individuals who knew exactly what to do, c) the ACRM training paradigm in which the simulations were conducted encourages distribution of workload and mobilization of help, tending to “level out” the technical performance.

Behavioral Processes in the Management of Abnormalities

A complementary evaluation used by some groups is to assess the quality of the cognitive and behavioral processes used by individuals and teams to recognize the abnormality and to direct the implementation of the technical management. The behavioral component of crisis management must however be assessed in a subjective

fashion. Two research groups (VA/Stanford and University of Basel) are studying adaptations of the anchored subjective rating scales developed by the NASA/University of Texas Aerospace Crew Performance Project.

The VA/Stanford group also studied the interrater variability of subjective ratings of behaviors on five point anchored scales⁸². Again, several tests of interrater reliability were used. With the most stringent test (S_{av} - equivalent to the kappa statistic) “fair” (0.2 - 0.4) to “moderate” (0.4 - 0.6) agreement was found for the behaviors considered most critical in crisis management (e.g. leadership, workload distribution, primary anesthesiologist overall, team overall). Other interrater reliability statistics showed even greater agreement. Although there was some difficulty in agreement on the operational definitions of each type of behavior, the investigators stated that the largest problem in achieving agreement was the high variability of each behavior over the course of a simulation scenario. For example, an anesthesiologist might show evidence of good communication at one instant, only to be shouting ambiguous orders into thin air at the next instant. Aggregating these behaviors into a single rating was extremely difficult, even for bounded time segments of the scenario. The investigators also showed that combining scores from any two raters had a very low probability of differing from the mean of five raters by more than one rating point, whereas any single rating could differ by that amount 14% of the time.

Using the mean of all five raters' scores there was much higher variability between teams in their crisis management behaviors⁸². Several teams (14% for cardiac

arrest, 28% for MH) had mean overall team ratings at the level of “minimally acceptable” or below – 1 or 2 on the five point rating scale –and the performance of the primary anesthesiologist was rated at or below this level even more frequently (21% for cardiac arrest, 35% for MH). The ratings for specific crisis management behaviors showed similar patterns.

The Danish group has also given a preliminary report on their attempts to validate subjective and objective evaluation parameters, a technique they name “PEANUTS” (Performance Enhancement in Anesthesia Using the Training Simulator) 83.

The interrater reliability of ratings of crisis management behaviors was not as strong as was hoped. However, these are assessments of very complex behaviors and actions, and it should not be surprising that ratings are difficult. In fact, the VA/Stanford results given above are considerably better than that found in recent assessments of the interrater reliability of mock oral examinations⁸⁴ (data from the actual ABA examinations are not available), and the VA/Stanford interrater reliability results are approximately the same as those found among peer-reviewers (prior to any discussion) of actual clinical care in cases “previously judged to involve a perioperative indicator (an event or action that leads to an adverse outcome)”⁸⁵. Thus the reliability of simulator-based ratings of crisis management behaviors appear to be on par with those measures currently representing the standard of performance assessment in the anesthesiology profession.

Simulator Patient Outcome as a Measure of Performance

Can the “clinical” outcome of the simulator's mathematical physiology predict how a real patient would have fared under that individual's care? In extreme cases this is likely to be true. A subject who demonstrates totally erroneous decision making (e.g. failure to defibrillate a simulated patient with ventricular fibrillation) will quickly allow the patient's state to deteriorate unmistakably. However, the mathematical models are not sufficient to predict what would happen to any actual patient after complex sequences of therapy and more subtle patient care judgements. Thus, the clinical outcome of the simulated patient is one datum that can be used in the needed to assess the performance of the anesthetist on a simulation scenario, but for the foreseeable future, any credible performance measurement technique must involve subjective and semi-objective judgements by clinical experts.

The results from the various simulation groups suggest that it should be possible to develop a reasonable set of performance measures of anesthetist skill using the simulator as a tool to present standardized patient scenarios. This set of tools would not be perfect, but would be likely to be as good as the tools currently used to make decisions regarding board certification and peer review of adverse events. A definitive study of these tools is in principle doable, but would require a very large number of subjects rated by multiple raters and would thus would be complex and costly. No funding agency has yet come forward to support such a definitive study. Incidentally, no existing performance measurement in health care has been subjected to such a costly, complete, and public validation.

Can Simulators Be Used for the Evaluation and Testing of Residents or Practitioners?

Anesthetists have discussed the possibility of using the simulator as a tool for examinations, either for graduation from a residency or for Board certification. This use would require further evaluation of the simulation scenarios and of the predictive power of the performance assessment tools used. A difficulty with using simulation for Board certification testing is that the OR equipment would rarely be the same as that used by the candidate, and the OR staff's operational protocols might differ from those familiar to the candidate. In the training situation these difficulties can be overlooked as part of the global "suspension of disbelief" needed to maximize the benefits of simulator training. In the test situation these differences can disadvantage some candidates. Perhaps this could be overcome by providing practice time to candidates in a standardized simulation setup identical to that of the testing center.

Despite these difficulties, it is likely that as the use of patient simulators becomes more widespread, anesthetists and other clinicians will become more interested in using them to assist in evaluating performance. The existing system of performance evaluation that uses a relatively haphazard system of subjective judgments of clinical competency in residency along with written or oral examinations, has itself never been validated. Many believe that the written examination does not correlate well with clinical ability, and the degree to which the oral examination process tests actual clinical skill is unknown. Simulation could offer candidates the ability to demonstrate the

clinical abilities in a controlled clinical domain, while still demonstrating their consulting and language skills through oral examination.

The first trials of evaluation using simulators may occur in situations for which the evaluation is a non-threatening critique or is graded “pass/fail.” Another situation would be for the evaluation of residents who have been placed on probation or for whom dismissal from the residency is already a distinct possibility. For these residents the “burden of proof” is on them to demonstrate their skills. The simulator might offer a more controlled environment for them to do so. The same could be true for practitioners who wish to return to clinical work after a hiatus.

The Future Of Patient Simulation In Anesthesia

The use of patient simulators has now grown beyond its initial phase as a purely experimental technology and modality to enter a new period of growth and consolidation. Although many questions remain unanswered about the impact of the technology there now seems little question that simulation will be a significant technique for education, training, and research within anesthesiology and in many other domains in health care. At the level of basic health care education, simulators have already begun to make their mark in applications aimed at professional students (e.g. medicine and nursing). The expansion of clinical training beyond anesthesiology, for resident physicians and for experienced clinicians (physicians, nurses, and combined teams) has been an important development. Not only has this brought the benefits of simulation-based training to these other health care settings, it has also

brought anesthesiologists to the forefront of issues related to education, training, and performance assessment. As the profession of anesthesiology has sought to redefine its role within health care, the emergence of anesthesiologists both as experts in the use of simulation and as experts in the cognitive skills of complex dynamic decision making has added another important role for the profession.

Over the last five years many anesthesia training programs have asked whether they need a simulator and can afford it. Probably half the training programs in the United States have simulators or have negotiated access for at least some of their trainees to other programs' simulators. With so many programs having simulators, others who have been reluctant in the past are beginning to see the value in acquiring them. The question now asked is whether the institution as a whole can benefit from the applications of simulation. In general both new and existing simulation centers are based on multidisciplinary applications and cost sharing, although often anesthesiologists play the dominant role in running the center. It is likely that simulation-based training, lead largely by anesthesiologists, will become a routine part of the initial and recurrent training of all clinicians who work in settings involving high complexity and dynamism.

The simulators themselves are undergoing a steady stream of enhancements and improvements. Although cost is a major impediment to achieving all the enhancements that are technically feasible, the feature list will probably expand without enormous changes in cost. There is a vigorous competition between multiple manufacturers of simulators at varying levels of fidelity and complexity. However, there are some

fundamental limits to how perfect the simulators can become. Unlike aeronautical engineers, physicians do not design and build the system they wish to model. The fundamental differential equations of fluid mechanics and aerodynamics are firmly established, allowing supercomputers to provide technically meaningful simulations as replacements for many wind tunnel tests. Furthermore, there still are wind tunnel tests as well as test flights of actual prototype aircraft. Sophisticated instrumentation can be built into test structures to define their behaviors accurately. Physicians and simulator engineers will never have this kind of knowledge about the human body.

The early 21st century will probably see VR simulations take over from computer screen and realistic simulations. However, the pace of VR development continues to be relatively slow. There is not yet a robust inexpensive platform for developing complex virtual worlds. Until such platforms are developed, perhaps for entertainment applications, VR systems will probably remain too complex and expensive to take over from current simulation modalities. In order to fully take over for the kinds of applications currently being performed with hands-on simulators, VR systems will have to allow nearly complete immersion into a multi-person artificial world, with replication of tactile, visual, and auditory stimuli. Nonetheless, within one or two decades reasonably priced VR systems will allow full immersion at which time virtual reality may become the norm for training in many complex work fields. Virtual reality technology could also change the nature of work itself.

Table 1

Features making simulation an excellent investigative tool:
<ul style="list-style-type: none"> • There is never risk to a real patient • Rare critical events can be simulated at will • Error evolution can be allowed without intervention • Cases can be repeated in an identical manner to multiple subjects • The causes of faults or pathological processes can be definitively known • The environment and subjects can be highly instrumented • Invasive probes may be inserted into the scenario • Archival records allow re-analysis of events
Features limiting the usefulness of simulation:
<ul style="list-style-type: none"> • Subjects know they are being evaluated, may exhibit artifactual behaviors such as hypervigilance or cavalier attitudes • Simulator fidelity may be inadequate to probe specific errors • The simulations may not include the underlying organizational systems and constraints of real clinical environments that might affect performance • Time in simulation laboratories is expensive

Figure Legends

Figure 1: The Anesthesia Simulator 3.0 is a menu driven program that uses additional popup windows to illustrate physical findings. Vital signs are updated continuously in the main window, and some monitor sounds are audible. The program display is in full color.

Figure 2: The Eagle Patient Simulator, configured in an operating room environment at the Simulation Center for Crisis Management Training, VA Palo Alto Health Care System. The operating room environment is duplicated in nearly every detail.

Figure 3: The graphically oriented interface of the Eagle Patient Simulator Instructor/Operator Station (IOS).

Figure 4: The METI Human Patient Simulator™, in use as a training device for a team of healthcare personnel.

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