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A Comprehensive Anesthesia Simulation Environment: Re-creating the Operating Room for Research and Training

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Simulation is used extensively in industries that involve routine, but risky activities. The authors describe an anesthesia simulation environment that provides a re-creation of the anesthesiologist's task environment in a real operating room. The system provides appropriate inputs to standard monitoring equipment in common use during anesthesia, including ECG (with arrhythmias); invasive systemic arterial, pulmonary arterial, and central venous pressures (all coupled to ECG arrhythmias); automated cuff blood pressure; pulse oximetry; mass spectrometry; breathing circuit spirometry; and oxygen analysis. An intubation/thorax mannequin allows tracheal intubation and tube manipulation, and provides for simulation of occlusion, malposition, or disconnection of the tracheal tube, as well as regurgitation of gastric contents. The simulation is comprehensive in that it is "hands-on" and requires actual performance of most interventions using actual equipment. The simulation is conducted by a systems operator and a simulation director; the latter also acts in the roles of surgeon and circulating nurse. The simulator outputs are determined by a "script" that defines the consequences of routine anesthetic actions and pre-established critical incidents. Decisions about timing and override of the script are made by the simulation director. This control system offers maximum flexibility while maintaining clinical realism. The simulator experiences were judged as highly realistic by 21 subjects. Limitations in this version have centered on the mannequin (*e.g.*, no patient movement, minimal or confusing physical signs) and will be addressed in future versions of the system. The authors suggest that anesthesia simulation can be accomplished at nominal expense and has major potential for training, continuing education, certification, and research. (Key words: Computer simulation.)

THE ADMINISTRATION of anesthesia, although frequently said to be "routine," requires both vigilance and the ability to handle problems that can be immediately life-threatening. These skills are also required in other pursuits, such as aviation, ship-handling, or nuclear power, where potentially risky activities are routinely carried out with relative safety. Simulators are used extensively in these fields[1–4] to train personnel for both routine and emergency operation. The technique is highly developed in aviation, where advanced technology provides extraordinarily realistic simulator systems for a substantial portion of the training and certification of airline pilots.[1,2]

Simulation training has been proposed[5,6]‡ as a means to reduce the incidence of anesthetic mishaps and their impact. However, there have been few documented attempts to implement physical simulator systems for anesthesia. Nearly 20 yr ago, the SIM 1 project[7,8]‡ produced a simulator system that partially mimicked the patient and the anesthesiologist's work-station, and was used to determine whether simulator training could speed certification of anesthesia residents in tracheal intubation. A non-significant trend to faster acquisition of competence was found[8] for the five residents who used it. However, SIM 1 did not provide *any* electronic or invasive monitoring (no ECG or transduced pressures), and could accommodate only six drugs (thiopental, succinylcholine, O_2, N_2O, cyclopropane, and other volatile anesthetics).

In the past 20 yr, both the practice of anesthesia and available technology have changed, making improvements over SIM 1 both necessary and possible. While others have produced simulators that utilize only a computer graphics screen,[5] we chose to implement a "hands-on" simulator that comprehensively re-creates the task environment of the operating room (OR), including manual and cognitive tasks of anesthesia administration, patient monitoring, and intervention. We have thus named our system the Comprehensive Anesthesia Simulation Environment (CASE—currently version 1.2).

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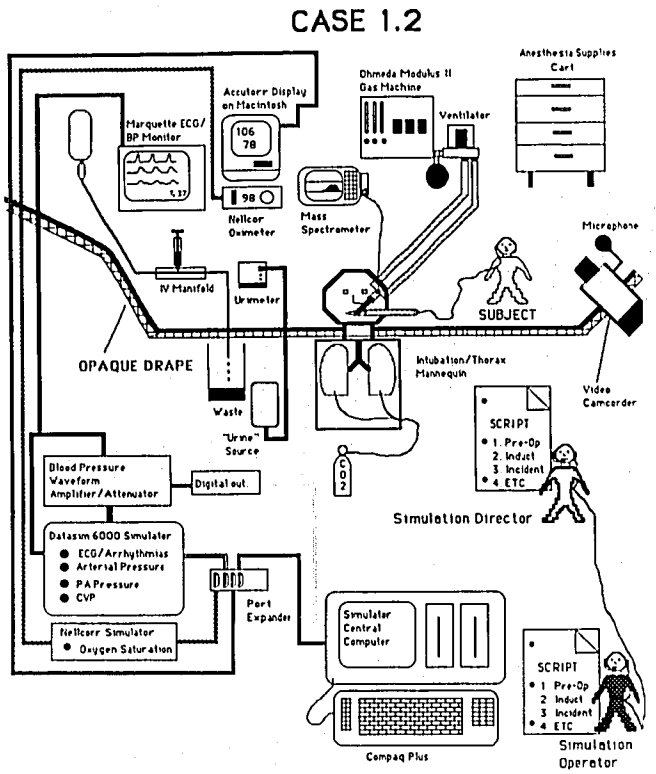

FIG. 1. Schematic diagram of the CASE 1.2 system. The simulator provides input to all significant patient monitors. A mannequin allows tracheal intubation and provides certain clinical signs. The system is coordinated by a central computer which is controlled by a simulation operator and an anesthesiologist simulator director working from a script.

Materials and Methods

DESIGN PHILOSOPHY

For a total simulation of the modern anesthesiologist's task environment provision of complete capabilities for invasive and non-invasive monitoring (ECG, intravascular pressures, oximetry, mass spectrometry, etc.) is essential. Added realism is provided by requiring that monitoring and other tasks be performed using standard operating room (OR) equipment wherever possible. Furthermore, commercially available "simulators" are used to provide waveforms and data to patient monitoring equipment. By using these devices and some custom interface electronics as subcomponents in the simulator system, we eliminate the cost and complexity of hardware and software to provide these waveforms from the main simulator computer.

A second essential characteristic of a comprehensive simulator is that it re-create the anesthesiologist's physical, as well as mental, task environment. Simulation takes place in a real OR, and the subject is required to physically perform tasks wherever appropriate, including airway and tracheal tube manipulation, physical examination, drug selection and administration, and equipment trouble-shooting. This heightens the realism of the simulation and forces the subject to reallocate time and attention when physically performing a task. Interaction with the "surgeon" is important both for acquisition of clinical information (which may be correct or misleading), and also because it is potentially distracting. The role of surgeon, and that of circulating nurse, are played by the simulation director.

CASE 1.2 (fig. 1) provides inputs to virtually all the monitors currently in common use during anesthesia.

ECG and Invasive Pressures. ECG and systemic arterial, pulmonary arterial, and central venous pressure waveforms are sent from a Datasim 6000 simulator (Medical Data Electronics, Arleta, CA) to a Surgical 7000RA monitor system (Marquette Electronics, Marquette, WI) (fig. 2). The Datasim 6000 provides multiple normal and abnormal rhythms with heart rates variable from 21 to 195 beats per minute in steps of approximately 7 beats per minute. It also provides multiple types of ectopic and irregular beats with automatic coupling of invasive pressure traces to ECG arrhythmias (fig. 2). While the Datasim 6000 provides incremental control of invasive pressure amplitudes, the transition between amplitudes is not clinically realistic. We therefore constructed a digitally controlled variable-gain amplifier/attenuator for each pressure channel, with an eight-bit digital line provided through a Series 500 Data Acquisition System (DAS; Keithley Instruments, Boston, MA). This allows beat-to-beat amplitude adjustment of mean arterial pressure from 0 to 190 mmHg in increments of 1 mmHg; similar adjustments for pulmonary artery and central venous waveforms are implemented with appropriate scale reductions (fig. 2).

Temperature. The Marquette monitor has inputs for two temperature probes, which are simulated to 0.1 degrees Celsius resolution (fig. 2) using manual ten-turn potentiometers.

Pulse Oximetry. Oximetry data are sent to a Nellcor™ N-100 pulse oximeter (Nellcor, Inc., Hayward, CA) from an oximetry simulator provided by the manufacturer. This provides a phasic waveform with adjustable O_2 saturation, pulse amplitude, and heart rate.

Non-invasive Blood Pressure. Since there is currently no satisfactory patient simulator available for non-invasive blood pressure, a functional replica of the Datascope Accutorr (Datascope, Inc., Paramus, NJ) is implemented on a Macintosh™ computer screen (Apple Computer, Cupertino, CA) programmed in PortaAPL™ (Portable Software, Cambridge, MA). The screen is functionally the same as that of the Accutorr and includes a displayed ramp-up and ramp-down of the

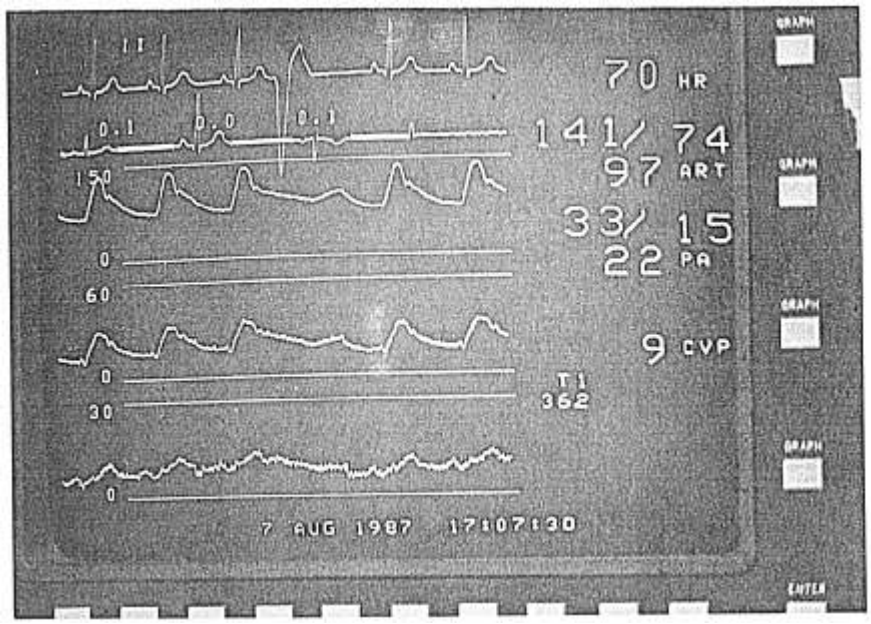

FIG. 2. Display of the main ECG/pressure/temperature monitor with simulator inputs. The top trace is the real time ECG, and the next trace is a representation of time averaged traces from leads I, II, and V with automatic ST segment analysis. Arterial, pulmonary arterial, and central venous pressures are shown. Note the reduced perfusion associated with the ectopic beat. Temperature is displayed at the bottom right.

cuff pressure during a measurement cycle. Operator choices (*e.g.*, alarm levels and cycle time) are identical to the Accutorr but are performed using a "mouse" and customized menus. This is the only monitor in our simulator which does not use standard equipment; the strong functional resemblance to the real device is adequate.

Sub-component Integration. Each of these sub-components is controlled *via* serial communications (RS-232C) from a central computer (Compaq Plus™, Compaq Computer, Dallas, TX) (fig. 1). A serial port expander (Logical Connection™, "Fifth Generation Systems," New Orleans, LA) provides communication with three (or more) serial devices. The central computer software is written in ASYST™ [9] (Macmillan Software™, New York, NY), which combines high-level computation with digital outputs *via* the DAS. Custom windows on the computer screen display the current values of all simulator-controlled variables. Software routines triggered by function keys allow the operator to change the value of any variable to one or several of the monitors at once. The software coordinates heart rate values to the three monitors that display it. A programmable statistical variability is provided for the oximeter and blood pressure cuff heart rates relative to the ECG derived rate. A similar coordination is implemented for arterial pressure values.

Mannequin. An intubation/thorax mannequin ("Eddie Endo," Armstrong Industries, Chicago, IL) is used for simulation of airway manipulations, including tracheal intubation. The mannequin has two "lungs" which we modified to allow unilateral bronchial occlusion by a balloon catheter, and a metered infusion of CO_2 *via* a small catheter to each "lung" to simulate normal metabolic production of CO_2. This allows the use of a capnograph, or, in our case, a mass spectrometer (SARA System, Allegheny International Medical Technology, St. Louis, MO), to monitor gases in a realistic fashion (fig. 3). Other features of the mannequin include breath sounds, which can be heard both on the chest and *via* an esophageal stethoscope; gastric regurgitation by pressurized infusion of colored liquid into the mannequin's esophagus; and urine output, simulated by a volumetrically controlled infusion of dyed solution into a urine measurement bag.

A standard Modulus II™ anesthesia machine (Ohmeda, Madison, WI) is utilized for gas flow and automatic ventilation. Because the mannequin's "lungs" have a volume and compliance roughly similar to that of a patient, airway pressures and spirometry readings are in the physiologic range. Venous or arterial cannulation procedures are not currently simulated, but intravenous tubing is provided which drains into a waste container and can be occluded or disconnected. Intravenous drugs must actually be drawn up and administered into a flowing iV to be effective. A standard multidrawer cart is used to provide all customary anesthesia drugs and supplies. Controlled drugs are simulated with labeled syringes containing saline, and outdated or discarded supplies are utilized whenever possible.

Initial set-up of the simulator system in an unused operating room takes approximately 20 min.

Scenario Control. The simulator must be able to respond dynamically to interventions by the subject. We present a scenario using a script that contains pre-defined sequences of events appropriate to the case and

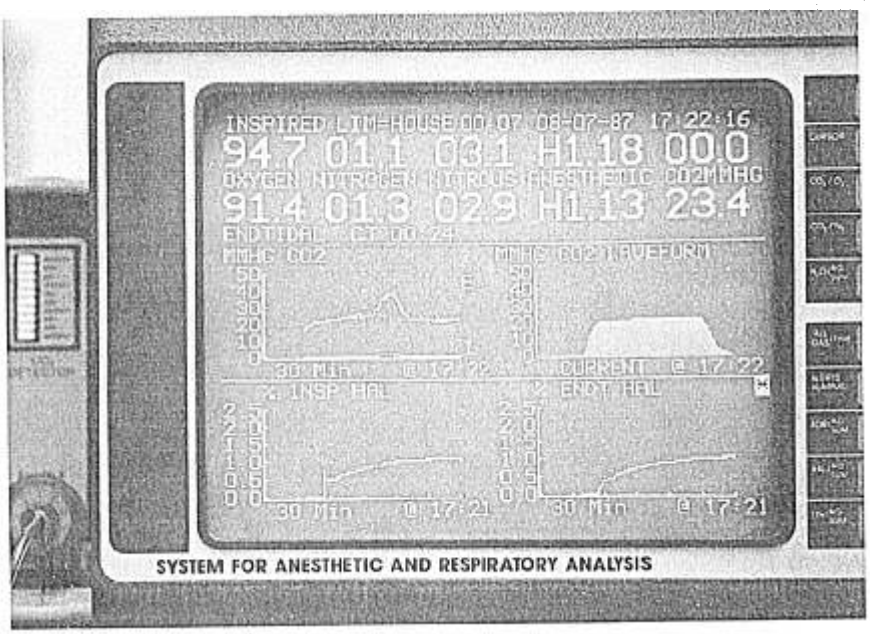

FIG. 3. The mass-spectrometer display during simulation. CO_2 is infused into the mannequin's lungs. Anesthetic gases are measured in the breathing circuit, including a gradient between inspired and expired concentrations (lower trend plots). The gradient is caused by equilibration of inspired gases within the breathing circuit and the mannequin's lungs.

problems to be simulated. Scenarios can include equipment faults, major and minor critical incidents (table 1 and Appendix), and medical judgement situations. The subject is given a data sheet describing the "patient's" history, physical examination, and laboratory results before the simulation.

TABLE 1. A Partial List of Situations Which can be Presented With CASE 1.2

Life-threatening	Non-life-threatening
Critical incidents	
Breathing circuit disconnect	ECG lead disconnect
Endobronchial intubation	IV disconnect or obstruction
Inadvertent extubation	Intravascular monitoring line failure
Kinked/obstructed tube	Minor failure (e.g. laryngoscope bulb)
O_2 failure	
Complete power failure	
Pathophysiologic states	
Tachycardia	Excessive anesthetic requirement
Bradycardia	Hypothermia
Hypertension	Pneumonthorax
Hypotension	Air Embolus
New Atrial Fibrillation	Pulmonary embolus
New ST segment changes (elevation or depression)	Malignant Hyperthermia
Congestive heart failure	Gastric regurgitation/ aspiration
Cardiac arrest	

In each script, anticipated actions and interventions are listed with the response of the simulator to each. The majority of subject actions are covered by the preestablished script; if other interventions or drugs are chosen, the script is superseded by the simulation director, who is a trained anesthesiologist. The simulation director and simulation operator are linked by a headset intercom (fig. 4), which allows private discussion of the subject's actions and the script recommendations. The time course of responses is determined primarily by the script and, wherever possible, is based on existing data.[10]

Twenty-two subjects (nine first year residents, nine second year residents, and four medical students who had completed an anesthesia clerkship) have undergone formal simulator sessions as part of a study of anesthesiologist problem-solving skills. A portion of one of these simulations is summarized in the Appendix. The average duration of the simulations was 1 h, 22 min (±17 min standard deviation), inclusive of machine checkout and equipment preparation. After each simulator session, the subjects were asked to complete a questionnaire concerning the realism of the simulator as well as provide any written comments on the experience.

Results

Seventeen subjects (six first year residents, nine second year residents, two medical students) returned evaluation questionnaires. The subjects' ratings of the realism of various aspects of the simulations are shown in

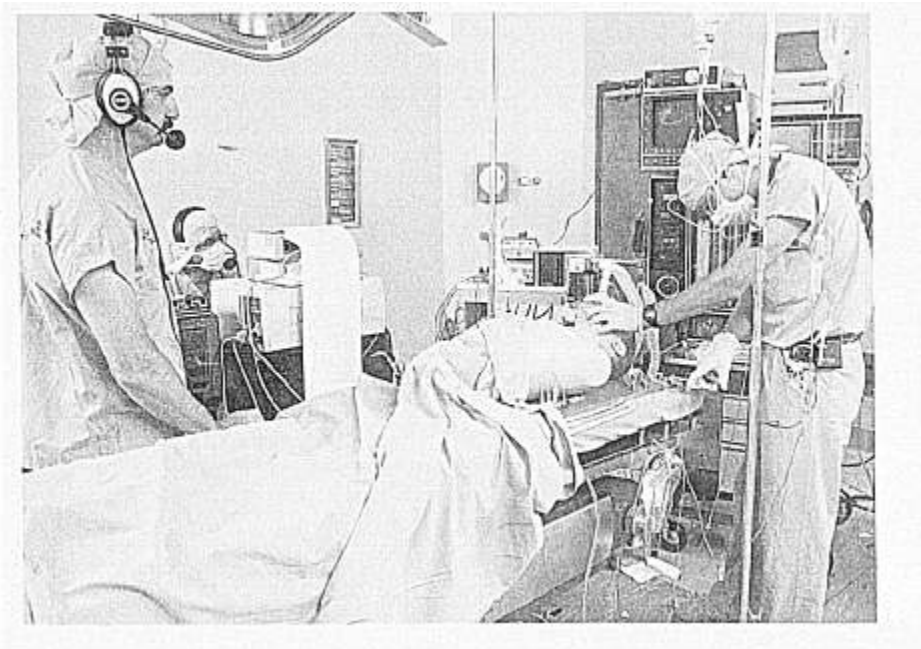

FIG. 4. Simulation in progress. The subject (right) is inducing anesthesia using intravenous agents as the simulation director (left) looks on. In the background, the simulation operator adjusts the inputs to the monitors. The simulation operator and simulation director are linked through a private headset intercom. An opaque drape ("ether screen") is placed just before commencing the "surgical" procedure.

table 2. The data indicate that the overall simulation scenario was considered realistic. The monitor information, simulator responses, and simulated incidents were judged as very realistic. The least realistic feature was clearly the mannequin, which gave inconsistent clinical signs (*i.e.*, breath sounds), and whoe airway did not satisfactorily simulate that of a patient (no spontaneous ventilation, difficult to ventilate with a mask and bag, unusual laryngeal "anatomy"). A partial list of the deficiencies of CASE 1.2 mentioned by the subjects is given in table 3.

Most subjects found the simulator session a challenging and valuable learning experience. A sample of their written comments in this regard are instructive:

"To date the most valuable education I've had." (Second year resident)

". . . illustrative of the limitations of relying on ready availability of attending physician." (Second year resident)

"It would become a great teaching tool. You're exposed to situations that you may not be exposed to in the average OR." (Medical Student)

"Good to be able to review myself in video." (First year resident)

Discussion

CASE 1.2 successfully reproduces most aspects of a patient undergoing general anesthesia (table 1). Its use of standard anesthesia equipment and techniques automatically makes incidental equipment failures or human/machine interaction errors possible. The system is highly flexible in simulating new or different scenarios because of its use of a script/human direction system.

Another recent anesthesia simulator,[5] implemented only on a computer screen, utilizes a sophisticated computer model of human physiology and pharmacology to determine kinetically and dynamically precise responses to "drugs" and "actions," which are input using a mouse on the screen. Interaction with the screen is drastically different than working with actual OR equipment, but there is currently no adequate way to

TABLE 2. Subject Evaluation of Simulation Realism

Aspect of Simulation	Realism Score* (N = 17)	
	Mean	Standard Deviation
Case presentation	9.0	±1.4
Anesthesia equipment	9.3	±0.59
Instrument readings	8.9	±1.0
Responses to drug administration	8.5	±1.3
Physioloic responses of simulator	8.1	±1.8
Mannequin		
Overall appearance	4.4	±2.7
Airway	5.2	±2.5
Responses	5.6	±2.6
Simulated incidents	8.2	±1.2

* Subjects were asked to "answer from 0–10: Zero = totally contrary to reality; 10 = complete duplication of reality indistinguishable from reality itself."

TABLE 3. Partial List of Deficiencies of CASE 1.2

Mannequin	No spontaneous ventilation Difficult to mask ventilate Jaw tension fixed No eyes No cyanosis, or sweating No heart sounds External breath sounds at limited sites No peripheral pulses No limbs Cold body surface
ECG/BP Monitor	Zero and Flush of invasive pressures poorly supported Systolic/diastolic pressure *ratio* is fixed ST segment changes cannot be superimposed on rhythms other than normal sinus rhythm Aberrant transition between heart rates <98 and >98
Non-invasive monitors	Oximeter pulse cannot track irregular beats Automated BP cuff is non-standard and requires "mouse" interface
Simulator control	Simulator staff in same room with subject Intravenous drug administration detected visually or by subject's report No failures *internal* to anesthesia machine Precise pharmacokinetic effects cannot be presented

input to the computer model all interventions of a human subject during "hands-on" activity. Furthermore, the model is based on response of the "average" patient, which may hamper presentation of unusual patient responses. Therefore, CASE 1.2 makes a trade-off against direct demonstration of precise pharmacokinetic aspects of drug action in favor of the flexibility of using a variety of techniques and drugs in a highly realistic environment. While the simulator responses generated by use of scripts in CASE 1.2 were judged highly realistic by our subjects, the use of computer models to determine simulator responses is a powerful tool that might eventually be adapted for use in a comprehensive ("hands on") simulator.

CASE 1.2 is inexpensive when compared with aviation simulators (which may cost $10 million). The total hardware cost of the simulator components is roughly $15,000 and could be substantially reduced with the use of a less expensive digital output board. Initial software costs have been approximately $3,000 primarily for acquisition of ASYST and APL.

The system interfaces directly to actual clinical equipment, eliminating the cost of procuring these items for the simulator, and taking advantage of underutilization of ORs in the afternoon, evening, and weekends. A similar approach has been successful in helicopter flight simulation (the TRIAD system).[2] Using actual clinical equipment does not allow simulation of internal anesthesia machine failures, since the clinical equipment must be kept fully safe and functional. But some equipment failures (*e.g.*, O_2 supply loss) can be presented by altering external attachments, and then certifying that they are properly restored before clinical use.

Each simulation currently requires two personnel, one of whom is an experienced anesthesiologist. If the system is used for training, this cost could be significant, but it depends critically on how simulator training is incorporated into a teaching program, since existing personnel already devote time to non-clinical resident and student training. The overall cost effectiveness of anesthesia simulation for training involves many factors and remains to be determined.

While CASE 1.2 is a major advance over SIM 1, and provides an operating room environment judged realistic, it is not yet an optimal simulation of the operating room. Many of the system's deficiencies (table 3) appear amenable to technologic solutions, which we will explore in future generations of the CASE simulation system.

There are several advantages of simulation in anesthesia: 1) there is no risk to a patient; 2) scenarios in-

TABLE 4. Examples of the Possible Uses of Simulation in Anesthesiology

Research
Response to critical incidents by anesthesiologists and nurse anesthetists
Utility of different display or alarm modalities
Effect of artifacts and false alarms on problem solving performance
Effect of fatigue and other stressors on anesthesiologist performance
Training
Introduction to anesthetic procedures for medical students and new residents
Recognition of and response to critical incidents
Recognition of monitor artefacts; use of redundant monitoring
Introduction to sub-specialty anesthesia protocols for advanced trainees
Practice working alone for residents about to enter practice
Testing
Routine in-training examinations
Assessment of trainees whose clinical competence is in question
Test of competence for higher responsibility positions (trauma coverage obstetric coverage, etc.)
Adjunct to board certification examinations
Periodic re-examination of practitioners

volving uncommon but serious problems can be presented; 3) the same scenario can be presented sequentially to multiple subjects; 4) errors can be allowed which in a clinical setting would require immediate intervention by a supervisor; 5) if desired, the simulation can be halted for teaching, and can be restarted to demonstrate different techniques; and 6) recording, replay, and critique of performance is facilitated using the simulator. The readily apparent disadvantage to simulation is that it is not reality; to whatever extent the simulation is not perfect, inaccuracies may result. Even in a perfect simulator, the subject knows it is a simulation, not a "real" situation, which can induce a variance from normal performance, either a heightened expectation of problems, or an excessively cavalier attitude.

Simulation may be useful in anesthesiology for research, training, or testing. In fact, our long-term objective in creating CASE 1.2 is to reproduce the task environment of the anesthesiologist as a research tool for investigating the cognitive processes of different anesthesiologists managing the same "patient," and responding to the same intraoperative critical incidents. A list of other possible uses for a comprehensive anesthesia simulator is given in table 4.

Anesthesia simulation is in its infancy and substantial research is needed to determine whether simulation will become an important tool in our profession. The example of aviation suggests that the tremendous potential of simulation as a tool for research into human factors, and for training, evaluation, and certification of professional personnel, can easily justify the effort.

The authors wish to thank Nellcor, Inc., for the use of their oximetry simulator.

ADDENDUM

A complete description of the non-commercial hardware and software used in CASE 1.2 is available at no charge from the author (David M. Gaba, M.D.). This includes: 1) a circuit diagram of the digitally controlled variable-gain amplifier/attenuator; 2) *source code* (in PortaAPL) for the Macintosh computer display of non-invasive blood pressure data; and 3) *source code* (in ASYST) for the simulator central interface which allows single point control of the multiple sub-simulators.

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Appendix

NARRATIVE DESCRIPTION OF A PORTION OF AN ACTUAL SIMULATION

The subject was a first year resident with 5 weeks of anesthesia experience. The scenario patient was a 65-yr-old man with chronic but stable angina and obstructive lung disease for a mastoidectomy. His room air oxygen saturation was 93%. Induction of anesthesia (26:00 min elapsed after beginning setup) was uneventful, although the "patient's" circulation reacted to laryngoscopy and intubation (HR increased from 70 to 100 and BP increased from 113/60 to 140/75). These parameters were easily controlled with N_2O and isoflurane, the table was turned 180°, and drapes were placed. The heart rate and blood pressure were increased after skin incision, but were reduced with aliquots of fentanyl and increased concentrations of isoflurane. At 55:00 min elapsed time the HR was 77, BP was 133/70, and O_2 saturation was 98% (with an $F_{I_{O_2}}$ of 40%).

At exactly 55:00 min, an event was generated by the simulator staff. At 56:15 min, the subject stated that all was stable, including the peak inspiratory pressures (PIP). He immediately (56:30 min) corrected himself, noting that the PIP had in fact increased to 45 (cm H_2O). He suggested that the endotracheal tube might be kinked, checked under the drapes, and warned the surgeon not to rest his hand on the tube. The PIP was still 45, however, so he checked the inflation pressure of the tube cuff, which he decided was OK. He hypothesized that the "tube might be in too far." Noting that the PIP was still 45, he wondered why bronchospasm had suddenly developed, and increased the isoflurane concentration, apparently deciding that inadequate depth of anesthesia might be responsible. Observing that the blood "pressure still looks good" and with a satisfactory waveform on the mass spectrometer, he then

noted that the CO_2 had increased a few mmHg, indicating that the patient was "not ventilating" as well as before, but that the saturation was "OK." At 58:00 min, the PIP was still 45 and the subject turned down the total gas flows, after which he noted that the PIP had decreased to 35. Finding that this action reduced the measured expired volume (electronic spirometer), he increased the ventilator rate, which reduced the expired volume even further. At this time (58:50 min), he noted the oxygen saturation at 95%. He again wondered about the endotracheal tube placement, and increased the FI_{O_2} to 50%. Noting that the BP had decreased (to 118/70), he decreased the isoflurane concentration. At 1:00:58 min, the oxygen saturation was observed at 93%, which puzzled him because he had "just increased the oxygen flow," although he observed that this was not yet confirmed on the mass spectrometer. At 1:01:22 min, he was again concerned about the decreasing oxygen saturation (now 92%). He checked the pulse in the foot, and was told it was normal. Noting again that the BP had decreased slightly, he increased the iv rate, and observed that the mass spectrometer now confirmed a higher FI_{O_2} and a lower end-tidal CO_2.

At 1:02:54 min, he checked the connections of the oximeter, and requested a change of the oximeter probe to the toe, but the value remained the same (91%). He noted that the BP was somewhat increased (140/90), but indicated that this would be acceptable. At 1:04:01 min, with the oximeter reading 90%, the subject decided to withdraw the tracheal tube. While under the drapes, he withdrew the tube 1–2 cm, and re-taped it. He checked the PIP, which was now 30, and the oxygen saturation, which was starting to increase. He informed the surgeon that the tube had been pushed into the right mainstem bronchus, most likely due to the movement of the head.

The event at 55:00 min simulated intubation of the right mainstem bronchus by inflating an occlusive balloon in the left mainstem bronchus of the mannequin. All CO_2 was shunted to the right lung. These actions were reversed when the subject withdrew the tube.