Anesthesiology
72:191–197, 1990

The Anesthesia Simulator-Recorder: A Device to Train and Evaluate Anesthesiologists' Responses to Critical Incidents

Howard A. Schwid, M.D.,* Daniel O'Donnell, Ph.D.†

The Anesthesia Simulator-Recorder is a computer program that trains and evaluates anesthesiologists' management of critical incidents. The program executes on IBM compatible personal computers, combining a graphic display of the operating room with mouse-driven input and using an integrated set of physiological and pharmacological models to predict patient responses. The program records the simulated patient's vital signs and all management decisions, and produces a printed case summary. The Anesthesia Simulator-Recorder was evaluated by 44 resident and attending anesthesiologists at seven different anesthesia training centers. These anesthesiologists found the simulator easy to use with clear presentation of the case and management options. The physiological and pharmacological models produced clinically realistic predictions of patient behavior (mean score = 8.5, where 10 is highly realistic and 1 is unrealistic). The Anesthesia Simulator-Recorder was appraised as an excellent training device (mean score = 8.5, where 10 is outstanding and 1 is poor) because it provides the ability to repeatedly practice the management of critical incidents. The simulator was judged to be a good evaluation device (mean score = 6.6, where 10 is outstanding and 1 is poor). No significant differences were found in evaluations between the institution where the program was developed and other institutions, or between residents and attendings. (Key words: Computer: simulation. Outcome: critical incidents.)

THE ANESTHESIA Simulator-Recorder is a computer program that simulates many of the physiologic and pharmacologic aspects of general anesthesia. The patient, anesthesia machine, monitors, and management options are presented by a graphic user interface that allows the trainee to simulate administration of an anesthetic. An integrated set of mathematical models predict patient responses to the anesthetic management and a finite state machine creates simulated critical incidents. In addition to simulating the events, the Anesthesia Simulator-Recorder prints a detailed summary of the case and the management for later review.

The Anesthesia Simulator-Recorder is designed as a teaching and evaluation tool. As a teaching tool, the program provides an interactive environment to practice management of cases and critical incidents. As an evaluation tool, it can simulate a critical incident and record the examinee's detailed response to it. These can later be reviewed and evaluated.

The Anesthesia Simulator-Recorder was tested by anesthesia residents and attendings at several anesthesiology training programs. Ease of use, predicted patient responses, and suitability for training and evaluation of response to critical incidents were assessed.

Methods

DESCRIPTION OF THE SIMULATOR-RECORDER

The Anesthesia Simulator-Recorder is an expanded version of a previously described anesthesia simulator[1] and has been redesigned to operate on an IBM AT compatible personal computer with 640 K RAM, a hard disk, EGA graphics, and a mouse. Major improvements include pharmacokinetics and pharmacodynamics for 48 additional drugs, ability to examine the simulated patient, use of additional monitors, and automatic recording of the patient's vital signs and trainee's management decisions. The program is written in TurboPascal, Version 4.0 (Borland International, Scotts Valley, CA). There are three important aspects to the program: user interface, mathematical models, and the printed case summary.

User Interface. The Anesthesia Simulator-Recorder was designed to be easily used by anesthesiologists having minimal computer experience. The display presents the operating room environment on the screen of a personal computer (fig. 1) with a simulated patient and monitors including the hemodynamic monitor, mass spectrometry, noninvasive blood pressure (NIBP), temperature, pulse oximetry, spirometry, and airway pressure. The anesthesia machine, vaporizer, ventilator, and iv fluids are also shown. The screen is continuously updated to present the condition of the patient by displaying digital values on the monitors and analog waveforms that sweep across the screen. In addition, moving flowmeter bobbins indicate the fresh gas flows and animated patient images exhibit the state of the airway.

The Anesthesia Simulator-Recorder describes a simulated patient to the trainee who plans and performs a general anesthetic. Using mouse-driven input, the trainee can examine the patient, communicate with the surgeon, manage the airway, control ventilation, and administer fluids and medications. The drugs included in the Anesthesia Simulator-Recorder are listed in table 1. The ex-

* Assistant Professor of Anesthesiology.

† Systems Analyst/Programmer.

Received from the University of Washington Department of Anesthesiology. Accepted for publication August 28, 1989. Supported in part by a grant from the Anesthesia Patient Safety Foundation. The Anesthesia Simulator-Recorder was awarded Best Scientific Exhibit at the New York State Society of Anesthesiologists Postgraduate Assembly, December 1988.

Address reprint requests to Dr. Schwid: Anesthesiology Service (112A), Veterans Administration Medical Center, 1660 South Columbian Way, Seattle, Washington 98108.

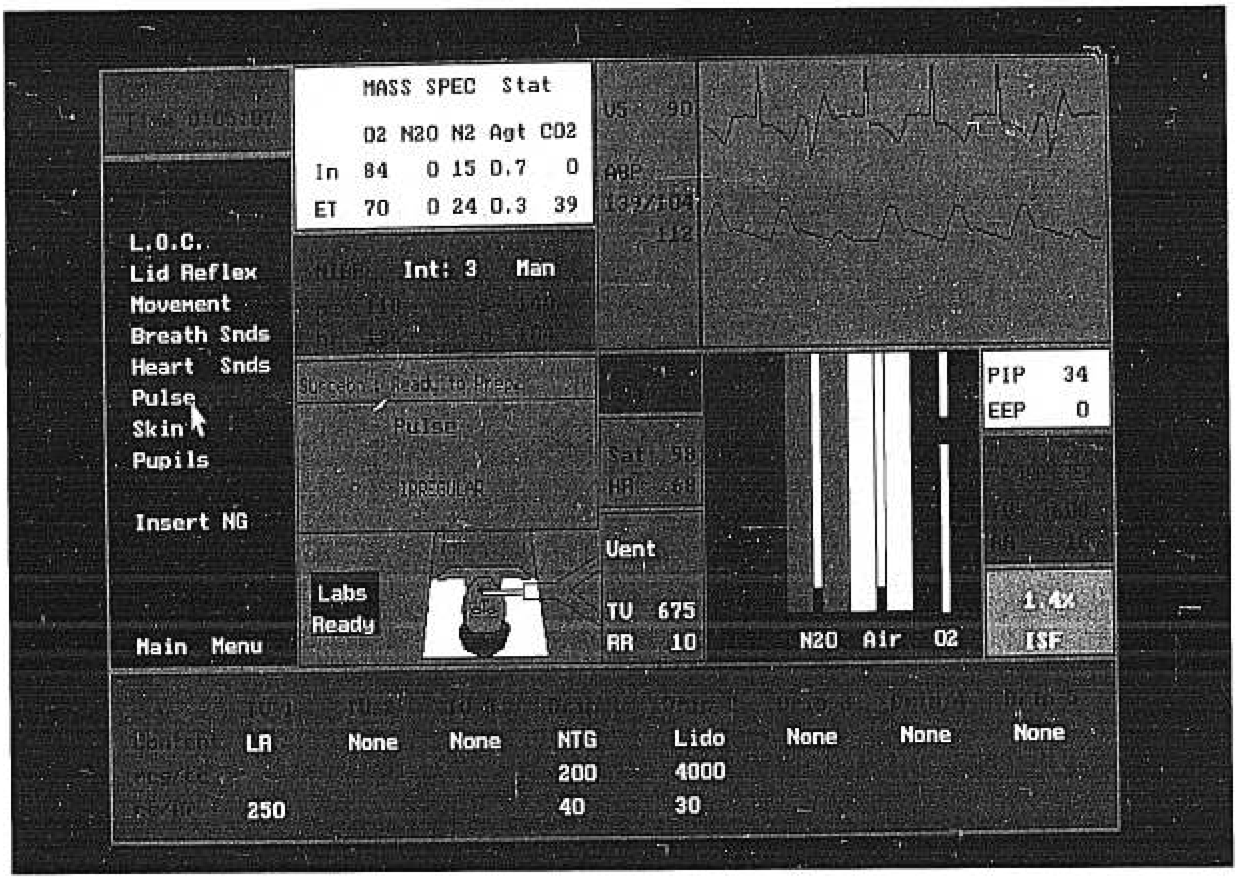

FIG. 1. The Anesthesia Simulator-Recorder display includes the patient, the anesthesia machine, and monitors. The patient's vital signs are shown on the monitors and messages describe physical signs. Management of the airway, fluids, and administration of drugs are controlled using a mouse.

aminee can also perform simulated Advanced Cardiac Life Support skills such as CPR, defibrillation, and the use of resuscitative drugs.

The simulated patient's vital signs are predicted in real time by the mathematical models. A critical incident can be created during the case and the response of the examinee is recorded. Several different patients and critical events are possible and the examinee does not know what critical event, if any, will occur during his management of the case. The critical incidents included in the Anesthesia Simulator-Recorder are listed in table 2.

Mathematical Models and Finite State Machine. The patient responses to the management are predicted in real time by a set of physiological and pharmacological models. The model of the cardiovascular system predicts cardiac output, blood pressures, and myocardial oxygen balance. The model of the respiratory system predicts airway pressures, gas exchange, blood gases, and uptake of inhalation agents. The pharmacokinetic model predicts plasma concentrations of the 53 drugs included in the simulator while the pharmacodynamic model predicts effector compartment drug concentrations and effects. The models are linked so that a disturbance in one system will influence another. For example, inadequate ventilation or oxygenation will cause release of endogenous catecholamines leading to tachycardia and hypertension.

A finite state machine[2] defines a finite number of clinical states such as myocardial ischemia or bronchospasm. The finite state machine defines characteristics of the state, and the factors that determine transition from one state to another. During the simulated case, a state can be entered by model prediction or by setting a critical incident timer. For example, the myocardial ischemia state will occur if the myocardial oxygen balance model predicts that myocardial oxygen demand exceeds supply. Alternatively, the myocardial ischemia state will be triggered several minutes after induction regardless of the anesthetic management if the critical incident is myocardial ischemia. Once the myocardial ischemia state is initiated, model parameters are adjusted to create premature ventricular contractions, decreased contractility and left ventricular diastolic compliance to reflect the physiologic effects of myocardial ischemia. Termination of the myocardial ischemia state will occur when manipulation of the hemodynamic parameters causes myocardial oxygen supply to exceed demand as predicted by the myocardial oxygen balance model. The finite state machine then resumes the normal state and eliminates the premature ventricular contractions, and restores myocardial contractility and relaxation properties.

The model of the cardiovascular system used in the Anesthesia Simulator-Recorder was described by Schwid *et al.*[3] It is a simplification of the model used by Fukui *et al.*[4] to study the effects of halothane on the circulation. The left and right ventricles are represented by the time-varying elastance (stiffness or inverse compliance) model that has been validated by the experimental work of Suga *et al.*[5] According to this model, the ventricles change their stiffness during the cardiac cycle with the maximum stiffness representing contractility.[6] The time-varying elastance model is described by:

$$P(t) = E(t) \cdot \{V(t) - V_d\} \quad (1)$$

where P(t), E(t), and V(t) are the instantaneous ventricular pressure, elastance, and volume, and V_d is the ventricular volume at zero pressure.

The diastolic or relaxation properties of the ventricles are described by an exponential function relating ventricular volume and pressure:

TABLE 1. Drugs Included in the Anesthesia Simulator-Recorder

Inhalation Agents	Cardiovascular Agents
Enflurane	Atropine
Halothane	Bretylium
Isoflurane	Calcium Chloride
Nitrous oxide	Dobutamine
IV Anesthetics	Dopamine
Diazepam	Ephedrine
Etomidate	Epinephrine
Ketamine	Glycopyrrolate
Midazolam	Labetolol
Thiopental	Lidocaine
Opioids	Nifedipine
Fentanyl	Nitroglycerine
Morphine	Nitroprusside
Sufentanil	Norepinephrine
Naloxone	Phenylephrine
Neuromuscular Agents	Propranolol
Antracurium	Verapamil
d-tubo Curare	Other Drugs
Metocurine	Aminophylline
Pancuronium	Beclomethasone
Succinylcholine	Cimetidine
Vecuronium	Diphenhydramine
Edrophonium	Furosemide
Neostigmine	Ipratropium
	Metaproterenol
	Methylprednisolone
	Metoclopramide
	Sodium Bicarbonate
	Sodium Citrate
	Terbutaline

TABLE 2. Critical Incidents

Airway difficult to manage
Esophageal intubation
Unintentional extubation
Obstructed endotracheal tube
Endobronchial intubation
Bronchospasm
Anaphylaxis
ST segment changes (myocardial ischemia)
Cardiac arrest
Breathing circuit disconnect
Vaporizer malfunction

$$P = b \cdot e^{k \cdot V} \quad (2)$$

where P and V are ventricular pressure and volume, and b and k are constants.[7]

The systemic and pulmonary vascular systems are represented by the modified Windkessel model.[8] Systemic and pulmonary venous compliances are included. The cardiac valves are represented by diodes which allow flow only in the forward direction. Given the heart rate, contractility, pulmonary and systemic vascular resistances, venous compliances, and intravascular volume, the cardiovascular model predicts filling pressures, cardiac output, systemic and pulmonary pressures using Euler integration.

Baroreflexes are also included in the cardiovascular model. Unless the reflexes are pharmacologically blunted, hypotension will cause an increase in heart rate, contractility, arterial, and venous tone.[9]

Myocardial ischemia is predicted using a previously described model of myocardial oxygen supply and demand.‡ In this model, the coronary vasculature is represented by a resistance and coronary blood flow is predicted from the integrated difference between the aortic pressure and the left ventricular pressure divided by the coronary resistance. Myocardial oxygen supply is predicted from coronary blood flow, hemoglobin concentration, and oxygen saturation. Myocardial oxygen demand is predicted from the left ventricular pressure-volume area that is defined by the instantaneous left ventricular pressure and volume as described by Suga *et al.*[10–12] If predicted demand exceeds supply, myocardial ischemia is predicted and the finite state machine causes disturbances in the heart rhythm, contractility, and diastolic relaxation. Failure to correct the myocardial ischemia within a few minutes causes the finite state machine to change the rhythm to ventricular fibrillation with complete loss of pumping function. Furthermore, the finite state machine requires correction of arterial blood gases, and appropriate doses

‡ Schwid HA, Buffington CW, Strum DP: Computer simulation of the hemodynamic determinants of myocardial oxygen supply and demand. The Journal of Cardiothoracic Anesthesia (in press).

of resuscitative medications and electrical cardioversion according to Advanced Cardiac Life Support guidelines for management of ventricular fibrillation to restore normal sinus rhythm.

The respiratory model includes gas transport through the anesthesia machine, circle system and airways, gas exchange, metabolic consumption of oxygen, and production of carbon dioxide. The three-compartment lung model which includes dead space, pulmonary shunt, and a pulmonary exchange unit[13] is used to predict gas exchange in a variety of pathological conditions. Conservation of mass equations are solved for each compartment and the Fick equation is used to predict exchange across the alveolar-capillary interface and the capillary-tissue interface:

$$\text{Quantity removed from blood} = [\text{blood flow}] \times [\text{arterial content} - \text{venous content}]. \quad (3)$$

Given the gas flows from the anesthesia machine plus tidal volume and respiratory rate, the respiratory model predicts inspired and exhaled gas concentrations and blood gases after each breath. Airway pressures are also predicted from airway resistance and total compliance.

Spontaneous tidal volume and respiratory rate are affected by many of the drugs used in the simulator. Respiratory depression is represented by changing the respiratory rate, decreasing the slope of the carbon dioxide response curve and increasing the apneic threshold.[14]

The pharmacokinetic model predicts plasma drug concentrations. For each drug administered, a two-compartment model is used with a central compartment and a peripheral compartment.[15] Standard pharmacokinetic parameters describe the volume of distribution, redistribution to and from the peripheral compartment, and clearance. The pharmacodynamic model predicts the drug concentration in an effector compartment as described by Sheiner and Stanski.[16] Each drug in the simulator may affect level of consciousness, analgesia, neuromuscular blockade, heart rate, contractility, systemic vascular resistance, venous tone, the baroreflex, respiratory rate, slope of the carbon dioxide response curve, and the apneic threshold. Forty variables are defined for each drug describing its pharmacokinetic and pharmacodynamic properties. These variables can be easily modified to produce patient variability in drug responses. (The author will provide on request the values used for the simulated patients in the Anesthesia Simulator-Recorder and references for these values).

Drug interactions are handled in an additive fashion with the effects of drugs A and B equal to the effects of drug A plus the effects of drug B. Drug agonism and antagonism are therefore simulated, but synergism is not yet included. A model for fluids predicts intravascular volume, urine output, electrolytes, and hematocrit from volumes administered and lost throughout the case.

Printed Summary. In addition to predicting and displaying the simulated patient responses, the Anesthesia Simulator-Recorder prints a summary of the case for later review. The record includes the patient's vital signs and the examinee's management. An example of the printed record for an uneventful induction is shown in table 3. Vital signs and respired gas concentrations are shown every 30 s along with a summary of all diagnostic and therapeutic decisions made during the case. As a testing device, the printed summary can be reviewed by a grader. As a teaching device, the reviewer can discuss management of the case at the end of a simulation session using the printed record, or temporarily suspend the simulation to discuss diagnostic and therapeutic options during the simulated case.

Evaluation of the Simulator

The Anesthesia Simulator-Recorder was evaluated by 44 anesthesia residents and attendings at the University of Washington, Mayo Clinic, Northwestern University, Pennsylvania State University, Hahnemann University, Emory University, and Brigham and Women's Hospital. These anesthesiologists used the Anesthesia Simulator-Recorder for at least 2 h and then completed a survey concerning the accuracy of the predicted patient responses and the utility of the program as a training and evaluation device. All critical incidents were evaluated. According to University of Washington guidelines, informed consent was obtained prior to the evaluation. Sixteen anesthesiologists were from the institution where the program was developed, while 28 were from other institutions. Twenty-one anesthesiologists surveyed were attendings and 23 were residents.

Results

Most of the anesthesiologists evaluating the Anesthesia Simulator-Recorder were able to use it to manage simulated cases in less than 30 min (19.8 ± 10.6 min, mean ± SD), and all learned to use it in less than 1 h (table 4). Although many of these anesthesiologists had no experience with computers, they found the mouse-driven input easy to use (8.7 ± 1.4, where 10 is very easy and 1 is difficult). Assessment of the graphical display showed it to clearly present the simulated patient's condition (8.0 ± 1.4, where 10 is perfectly clear and 1 is poor). Likewise, the predictions of the patient's responses to management by the physiological and pharmacological models were judged to be realistic (8.5 ± 1.0, where 10 is highly realistic and 1 is unrealistic).

The Anesthesia Simulator-Recorder was rated highly (8.5 ± 1.2, where 10 is outstanding and 1 is poor) as an instructional device. Evaluators stated that the most valu-

TABLE 3. Sample Printout of a Case Summary for an Uncomplicated Induction

Time	HR	ABP	CVP	PAP	PAOP	CO	RR	TV	PIP	EEP	O_2 Sat	O_2 In	Ag In	Ag Et	CO_2 Et
0:00:21 NIBP: Set measurement interval to every 3 min Mask placed. NIBP: Set measurement interval to every 1 min O_2 flow rate: 5.6 l/min	108	98/65/73	8	31/13/20	7	5.1	18	333	0	0	97	21	0.0	0.0	0
0:01:01 Fentanyl: 250 μg	100	105/69/78	8	32/14/21	7	5.2	18	304	0	1	97	70	0.0	0.0	37
0:01:34 Curare: 2 mg	99	106/69/79	8	32/14/20	7	5.1	18	288	0	2	98	76	0.0	0.0	33
0:02:07 Thiopental: 300 mg Sux.: 120 mg Sellick on.	97	107/72/80	8	32/13/20	7	5.1	13	251	0	2	98	81	0.0	0.0	35
0:02:39 L.o.c.: No Response Pulse: Strong Skin: Normal Lid reflex: Absent Train-of-Four: Absent Rhythm Change: Precursor	97	108/71/79	8	32/13/20	7	5.1	5	141	0	2	98	86	0.0	0.0	39
0:03:12 Rhythm Change: Normal Sinus Intubation successful. MAC 3 Size 8.0 Ventilation: Assisted TV 550 RR 8 Breath sounds: Clear	98	105/70/78	7	30/13/19	6	5.1	0	0	0	2	98	91	0.0	0.0	0
0:03:44 N_2O flow rate: 3.2 l/min O_2 flow rate: 1.6 l/min Vaporizer: ISF 1.5% Surgeon: prep Breath sounds: Clear Pulse: Strong Skin: Normal Pupils: 2 mm and reactive	101	99/66/74	6	28/12/18	6	4.8	8	495	30	2	98	92	0.0	0.0	41

able educational experiences using the program were practicing the management of critical incidents and the discussions about management stimulated by the cases. The Anesthesia Simulator-Recorder was appraised as a good evaluation device to test anesthesiologists' responses to critical incidents (6.6 ± 2.0, where 10 is outstanding and 1 is poor). No significant differences were found between evaluations at the institution where the program was developed and other institutions (table 4), or between anesthesia residents and attendings (table 5).

TABLE 4. Evaluations: University of Washington *vs.* Other Institutions

Evaluation Item	Total	UW*	Others
Number	44	16	28
Time to learn (mean ± SD)	19.8 ± 10.6	20.6 ± 10.3	19.3 ± 10.7
Mouse input	8.8 ± 1.4	9.6 ± 0.6	8.3 ± 1.5
Graphics display	8.0 ± 1.4	8.3 ± 1.4	7.8 ± 1.4
Accuracy of predictions	8.5 ± 1.0	8.4 ± 1.5	8.5 ± 0.6
Teaching device	8.5 ± 1.2	9.2 ± 1.1	8.2 ± 1.0
Evaluation device	6.6 ± 2.0	7.3 ± 2.0	6.1 ± 1.8

Discussion

Although a quantitative assessment of anesthesia risk can only be estimated, it is recognized that anesthesia does have potential risks and complications. Gaba described how many of the lessons learned from other high-risk industries can also be applied to anesthesiology.[17] Complex systems such as nuclear power, aviation, and space

TABLE 5. Evaluations: Residents *vs.* Attendings

Evaluation Item	Residents	Attendings
Number	23	21
Time to learn (mean ± SD)	20.9 ± 11.0	18.6 ± 9.9
Mouse input	8.5 ± 1.6	9.0 ± 1.0
Graphics display	7.7 ± 1.6	8.3 ± 1.1
Accuracy of predictions	8.4 ± 1.2	8.6 ± 0.7
Teaching device	8.4 ± 1.1	8.7 ± 1.2
Evaluation device	6.5 ± 1.9	6.7 ± 2.0

flight are prone to system accidents involving multiple interacting failures.[18] Operators of complex systems work from a "mental map" of the system, making management decisions based on the underlying map. It has been shown that even highly skilled professionals may construct an erroneous mental map of the situation and respond inappropriately to an emergency.

Cooper's studies of critical incidents during anesthesia[19] suggest that at least 33% of incidents are due to errors in judgement, confirming that anesthesiologists may often operate from faulty mental maps. Further evidence of management errors by anesthesiologists in a crisis situation are provided by the observations of Allnutt that in an emergency situation a hypothesis may be quickly formed and a great deal of information subsequently misinterpreted to support the initial, possibly erroneous, hypothesis.[20] Norman similarly implicates information overloading as a contributor to mismanagement of clinical emergencies.[21]

In order to develop correct working mental maps of the events surrounding potential catastrophes, simulation is widely used in several high risk industries. Simulation can be applied equally well to anesthesiology by creating emergency situations, providing the opportunity to practice management. The comprehensive anesthesia simulation environment developed by Gaba and DeAnda[22] uses a mannequin, real operating room equipment, and technical personnel to simulate cases. Despite a few deficiencies, this simulation environment was judged to be very realistic by medical students and residents. The Anesthesia Simulator-Recorder uses computer models and graphics to simulate clinical situations. Since it operates on a personal computer without the need for other equipment or personnel, the Anesthesia Simulator-Recorder is more accessible to clinicians and less expensive than the comprehensive anesthesia simulation environment.

The Anesthesia Simulator-Recorder, with physiological and pharmacological models, finite state machine, mouse-driven input, graphical display, and case summary printout, is a unique and sophisticated educational environment. It is easy to use, requiring only a small investment of time to learn to operate, even for anesthesiologists with no computer experience. It presents clinical scenarios clearly and the printed summary serves as a method to review the management following the case. It provides the ability to practice the management of life-threatening critical incidents. These are emergencies that every anesthesiologist should be able to manage "instinctively and flawlessly,"[19] but without a simulator may never encounter them in routine clinical practice, and cannot, therefore, be expected to have developed a reflex management plan. Practice with simulated critical incidents may prove to form a solid foundation for anesthesiologists to construct their own "mental map" of the crisis and appropriate management algorithms.

The Anesthesia Simulator-Recorder shows promise as a testing device for the management of critical incidents. Since a crisis is often anticipated during a simulation,[22] a prediction of vigilance in the operating room cannot be adequately assessed in a simulator. However, once the examinee observes a situation, each diagnostic and therapeutic step of the critical incident management is recorded by the Anesthesia Simulator-Recorder and can be graded. It should be clear that the Anesthesia Simulator-Recorder tests only cognitive skills, not manual skills. Furthermore, the evaluators felt that an examinee must be thoroughly familiar with the commands and messages of the simulator to avoid misinterpretation thus invalidating the test. Several evaluators stated that absence of auditory feedback for the pulse oximeter information and monitor alarms was a major drawback for use as an examination device.

Since educational computer programs have typically had difficulty being accepted outside the developing institution, it is important to note that evaluation results were similar for the Anesthesia Simulator-Recorder at several different institutions. Further studies of the simulator are planned at several institutions to assess the impact of the Anesthesia Simulator-Recorder on residents' anesthesia knowledge test and in-training exam scores, and to evaluate the ability of residents and practicing anesthesiologists to manage critical incidents, the kinds of mistakes made, and the ability to improve management with training on a simulator.

Several improvements in the Anesthesia Simulator-Recorder are planned to make it a better educational aid. A library of patients will be added to demonstrate the effect of disease states on pharmacokinetics and pharmacodynamics, including cardiac, pulmonary, renal, and hepatic disorders. Time acceleration will be added so that an hour of time can be presented in 1 min, providing the ability to compare several different anesthetic techniques for long cases without consuming hours of the anesthesiologist's time. Context-sensitive assistance will also be added to allow the anesthesiologist to ask for advice from an expert consultant for diagnostic and therapeutic management options or descriptions of the relevant physiology or pharmacology during for the simulated clinical situation.

The authors wish to thank Dr. David Strum for his design suggestions for the simulator display; Dr. Ronald Faust of the Mayo Clinic, Dr. Edward Brunner and Dr. Steele Holly of Northwestern University, Dr. Arthur Schneider of Pennsylvania State University, Dr. David Seitman of Hahnemann University, Dr. Joseph Garfield of Brigham and Women's Hospital, and Dr. Arnold Berry of Emory University for arranging the evaluations at their institutions.

References

1. Schwid HA: A flight simulator for general anesthesia. Comput Biomed Res 20:64–75, 1987

2. Hopcroft JE, Ullman JD: Introduction to Automata Theory, Languages, and Computation. Reading, Addison-Wesley, 1979, pp 13–54
3. Schwid HA, Taylor LA, Smith NT: Computer model analysis of the radial artery pressure waveform. J Clin Monitor 3:220–228, 1987
4. Fukui Y, Smith NT: Interactions among ventilation, the circulation, and the uptake and distribution of halothane—Use of a hybrid computer multiple model. ANESTHESIOLOGY 54:107–118, 1981
5. Suga H, Sagawa K. Instantaneous pressure-volume relationships and their ratio in the excised, supported canine left ventricle. Circ Res 35:117–126, 1974
6. Suga H, Sagawa K, Shoukas AA: Load-independence of the instantaneous pressure-volume ratio of the canine left ventricle and effects of epinephrine and heart rate on the ratio. Circ Res 32:314–322, 1973
7. Glantz SA, Parmley WW: Factors which affect the diastolic pressure-volume curve. Circ Res 42:171–180, 1978
8. Westerhof N, Elzinga G, Sipkema P: An artificial arterial system for pumping hearts. J Appl Physiol 31:776–781, 1971
9. Sagawa K: Baroreflex control of systemic arterial pressure and vascular bed, Handbook of Physiology, Section 2: The Cardiovascular System. Edited by Shepherd JT, Abboud FM, Geiger SR. Bethesda, American Physiological Society, 1983, 453–496
10. Suga H, Hayashi T, Shirahata M: Ventricular systolic pressure volume area as a predictor of cardiac oxygen consumption. Am J Physiol 240:H39–H44, 1981
11. Suga H, Hayashi T, Shirahata M, Suehiro S, Hisano R: Regression of cardiac oxygen consumption on ventricular pressure volume area in dog. Am J Physiol 240:H320–H325, 1981
12. Suga H, Hisano R, Goto Y, Yamada O, Igrashi Y: Effect of positive inotropic agents on the relation between oxygen consumption and systolic pressure volume area in canine left ventricle. Circ Res 53:306–318, 1983
13. Riley RL, Cournand A: "Ideal" alveolar air and the analysis of ventilation-perfusion relationships in the lungs. J Appl Physiol 1:825–847, 1949
14. Hickey RF, Severinghaus JW: Regulation of breathing: Drug effects, Regulation of Breathing, Part III. Edited by Hornbein TF. New York, Marcel Dekker, 1981, pp 1251–1312
15. Hull JC: Pharmacokinetics and pharmacodynamics. Br J Anaesth 51:579–594, 1979
16. Sheiner LB, Stanski DR, Vozeh S, Miller RD, Ham J: Simultaneous modeling of pharmacokinetics and pharmacodynamics: Application to d-tubocurarine. Clin Pharmacol Ther 25:358–371, 1979
17. Gaba DM, Maxwell M, DeAnda A: Anesthetic mishaps: Breaking the chain of accident evolution. ANESTHESIOLOGY 66:670–676, 1987
18. Perrow C: Normal Accidents. New York, Basic Books, 1984, pp 78–90
19. Cooper JB, Newbower RS, Kitz RJ: An analysis of major errors and equipment failures in anesthesia management: Considerations for prevention and detection. ANESTHESIOLOGY 60:34–42, 1984
20. Allnutt MF: Human factors in accidents. Br J Anaesth 59:856–864, 1987
21. Norman J: Education in anaesthetic safety. Br J Anaesth 59:922–927, 1987
22. Gaba DM, DeAnda A: A comprehensive anesthesia simulation environment: Re-creating the operating room for research and training. ANESTHESIOLOGY 69:387–394, 1988