

Simulation in Medical Education: Focus on Anesthesiology

D. John Doyle, MD PhD FRCPC

Department of General Anesthesiology
Cleveland Clinic Foundation

Abstract: Simulation refers to the artificial representation of a complex real-world process with sufficient fidelity to achieve a particular objective, usually for the purposes of training or performance testing. While simulation has been important from early times (as in the rehearsal of animal hunting activities or preparing for warfare), the needs of World War II greatly accelerated simulation technology for use in flight training. With the available of inexpensive computer technology in recent years, simulation technology has blossomed again, especially in the field of medicine, where applications range from scientific modeling to clinical performance appraisal in the setting of crisis management.

This article presents an overview of the application of computer-based simulation to medicine, focusing on anesthesiology and critical care medicine, including discussions on physiological and pharmacological simulation, virtual experiments, software only clinical simulators, and specialized hardware/software simulators for specialty teaching, as in airway management and in regional anesthesia. While many successes in using simulation in medical education can be identified, because the field is quite young, much remains to be done to demonstrate the scientific and clinical utility of simulation technology, especially in the context of the Fitzpatrick model of program evaluation.

Simulation refers to the artificial (and almost always simplified) representation of a complex real-world process with sufficient fidelity to achieve a particular goal, such as in training or performance testing. Simulation has likely been a part of human activity since early times. Simulation has long been important in a number of kinds of technical or professional training. For instance, the rehearsal of animal hunting activities and of warfare was a likely occasion for simulating the behavior of prey or enemy warriors. Simulation using technology probably dates back to Roman times or earlier. Good and Gravenstein¹ point to the Roman quintain (a post or an object mounted on a post, used as a target in tilting exercises) as a device that crudely but effectively simulated the behavior of an opponent during sword fighting. If the swordsman did not duck at the appropriate time after striking a blow, he would be hit by the quintain.

In modern times, preparation for war has been a powerful stimulus to the development of simulation technologies especially for aviation. Although some aircraft simulators were built as early as the pre World War I era, none of these early "static" models could provide the proper "feel" of the aircraft because they could not dynamically reproduce its behavior.²

However, in 1930 Edwin Link filed a patent for a pneumatically driven aircraft simulator that heavily influenced the development of simulation in aviation. The "Link Trainer", as it was known, soon became a standard tool for flight training before World War II; the onset of the war greatly accelerated its use as well as the further development of flight simulation technology in general.

In the 1950s, advances in electronic technology lead to electronic controls replacing pneumatic systems. With the advent of computer technology the aircraft simulator achieved the beginnings of its current form in the 1970's, but it has been continuously refined, as computer technology has advanced. At the moment these simulators are so realistic that pilots are routinely certified to fly new aircraft (i.e., obtain a "type rating") without actually having ever entered the real aircraft!

Another area where simulators have been used extensively is in nuclear power plants. One of the key factors that determines the safety of a nuclear power plant is the training and technical knowledge of its reactor. Simulators provide training tools for reactor operators in normal operations, as well as in training for responding to emergency situations.³

Computer-Based Simulation in Medical Education

In recent years simulators have seen increasing

discussed include physiological and pharmacological simulation, anesthesia and critical care simulators, as well as simulation in trauma, airway management and regional anesthesia. In all cases, the simulations

Table 1 – Selected Goals and Applications of Simulation in Medicine

- Teaching and training
 - Technical procedures (e.g., insertion of vascular catheters).
 - Heart sounds and lung sounds.
 - Interactive physiological modeling.
 - Avoiding the need for animal experimentation in biological and medical education (e.g., teaching sessions concerning cardiopulmonary physiology or pharmacology).
 - Reducing the need for clinical training using real patients in socially difficult situations (breast examination, pelvic examination, rectal examination).
 - Practicum for medical students during anesthesia or emergency medicine rotations.
- Human performance evaluation (e.g., responding to simulated critical incidents in the emergency room or operating room)
- Human factors engineering and usability engineering studies for medical equipment.
- Studies in cognitive engineering (e.g., development of cognitive process models).

use in training health care providers. Although the origins of computer simulation in medicine date back some four decades⁴, it is only now, with the advent of inexpensive computers, that this field has really taken off.

are computer-based. Simulation technology based on computers is just one of many applications of computers in medicine (see Table 2).

Computer-based simulators used in medical education fall into four general categories: (1) Screen-

Table 2 - Applications of Computers in Medicine and Anesthesiology

- Medical simulation
- Computer-controlled drug administration
Speech synthesis (e.g., warning messages)
- Speech recognition (e.g., dictating clinical notes, controlling voice-controlled machinery)
- Clinical algorithm implementation (e.g., helps you manage low airway pressure situation)
Critiquing systems (e.g., comment on choice of drug or technique)
- Patient information / computer-assisted preanesthesia interview (health questionnaire)
Operating room scheduling / physician on-call scheduling
- Computer-assisted learning / medical education
Servoanesthesia
- Automated anesthesia record management
- Anesthesia research: statistics, spreadsheets etc.
- Mathematical modeling of oxygen transport, hemodynamics, pharmacokinetics, etc.
Ergonomics / human factors / smart alarms / cascading alarms
- Clinical decision support / trending and tracking / early warning systems

This paper is concerned with presenting an overview of the issues in the use of simulators in medicine (see Table 1), with a particular focus on simulation anesthesiology and critical care medicine. Topics

based text simulators, (2) Screen-based graphical simulators, (3) Mannequin-based simulators, and (4) Virtual reality trainers.

Screen-based text simulators create verbal scenarios in which the user picks one of several responses and, based on the chosen response, a new text scenario is produced. For instance, in a scenario involving a patient presenting with a severe headache, the user may be offered options such as prescribing an analgesic such as Tylenol or getting a CT-scan of the head. Based on the user's choice, a new narrative is then generated and more management choices are offered. Being purely text-based, screen-based text simulators are relatively simple to construct and require little memory, making them popular in early medical simulation efforts. However, since they are lacking in graphical elements, they are rarely used today.

Screen-based graphical simulators such as 'Gasman' and 'Body'^{5,6} aim to recreate elements of reality in graphic form on a computer screen, often to elucidate the pharmacokinetic and pharmacodynamic processes associated with drug administration. Usually, only a mouse interface is involved. While these simulations help one understand the conceptual theory underlying clinical practice, they usually do not confer actual practical skills. Their strength lies in an ability to help one understand abstract concepts while remaining portable and relatively inexpensive. These simulators are particularly well-suited to physiological and pharmacological modeling (*vide infra*).

Mannequin-based simulators come in various levels of complexity, but are almost always expensive. The advanced models include a physical model of the human body and provide continuous signals representing physiological parameters such as electrocardiogram, blood pressure wave, capnogram signal and pulse oximetry signal. While some earlier systems required the intervention of a trainer to actively 'stage manage' the scenario in response to interventions, others make use of complex computer models of human physiology and pharmacology to automatically generate appropriate responses in the mannequin and signal outputs.⁷ In contrast to screen-based simulations, these simulators appear to recreate enough elements of reality to allow the acquisition of skills that are transferable back to the clinical environment.

Virtual reality trainers are just beginning to gain popularity, especially amongst surgical trainees. They offer a transition from the two-dimensional world of the textbook to the three dimensional world of simulated patients. The principle problem so far has been the lack of reality modeling in terms of offering a tactile 'feel'. However, this problem is being actively

tackled in research centers using micro-engineering techniques.

Early work on physiological modeling and simulation followed the advent of digital computers in academic medical centers and universities. For instance, Guyton and others^{8,9} have been using mathematical models of complex human physiology for years to help predict complex interactions of different organ systems. Even before that, Dickinson¹⁰⁻¹⁴ worked on educational physiologic models in the 1970s.

The Mechanical Ventilation Simulator (<http://www.ajdcomputing.com/pccm>) is one example of a simulation intended to enhance the teaching of the principles of mechanical ventilation to medical students and other individuals. The simulation allows the student to manipulate the ventilator settings of a hypothetical patient and see the results of the blood gases and other physiologic data. Such simulations are usually based on an explicitly expressed mathematical model.

In general, two steps are involved in the development of satisfactory computer models for physiological and pharmacological applications: (1) the development of a mathematical model that describes the behavior of the processes involved; and (2) translation of the model into a computer programming language or spreadsheet. Not infrequently, the models involve the solution of a system of differential equations.

Although many physiological problems are readily solved by direct analytical methods, not infrequently their solution is hampered by non-linearities, self-referencing (circular) equations, or other complexities. (An example of a non-linearity is the equation $y = x^2$; an example of a self-referencing equation set is the equation pair $y = 1/x$; $x = y + 1$.) Many conventional spreadsheet programs (e.g. early versions of Microsoft Excel) are poorly equipped to solve systems of this kind, not being generally designed for iterative equation solving methods.

One popular way to solve modeling problems is to write special programs in BASIC, C or even JavaScript. Spreadsheet programs that support iterative equation solving could also be used. For serious modeling problems Matlab, Mathematica, MathCAD and TK-Solver are popular packages to consider.

There are many questions in physiology that are not easily answered by direct experimentation, either because it is impractical, or impossible, to control all

the pertinent variables or because of ethical considerations. Consider the case of studying the influence of blood hemoglobin concentration on pulmonary gas exchange indices. It would be difficult to rigorously control cardiac output, total body oxygen consumption, and other variables to experimentally study the issue, while modeling the problem using simple equations offers several advantages:

- It relies on well-established physiological relationships (e.g. alveolar gas equation, pulmonary shunt equation).
- It permits insight into physiological issues not generally attainable in other ways.
- It is inexpensive
- It potentially reduces the need to carry out animal experimentation.

Three drawbacks to the virtual experimentation exist and must be reviewed with each model developed:

- The method is no better than the equations upon which it is based.
- The method may not be convincing to those physiologists who are not satisfied until confirmatory conventional experimental results become available.
- Errors can occur in model building (e.g., design error, programming error).

Finally, note that one potential difficulty with all such modeling methods is that the obtained results may depend critically on the equations used. In cases where the equations are known from first principles (e.g. alveolar gas equation, pulmonary shunt equation) this need not be an issue, but where an equation is empirical, alternative equations may possibly produce differing results. One example is the equation for the oxyhemoglobin dissociation curve, which has many competing formulations.

Where more than one set of equations exist to describe a physiological relationship, one can explore the effect of equation choice on the way the model behaves. One would expect however, that if several equations existed that all did a good job of representing the underlying data, that equation choice would generally not have a great influence on obtained results. By conducting virtual experiments, in the case of a few days (or even a few hours) one can obtain meaningful information about the interaction of several physiological variables, provided that the relationships describing the variables are available in equation form. By contrast, actual real experimen-

tion takes time, funds and effort that may not always be available. In fields such as oxygen transport, many relevant equations are simple and well-known, such as:

- Alveolar gas equation
- Pulmonary shunt equation
- Oxyhemoglobin dissociation curve
- Oxygen transport parameter definitions

To the extent that one accepts these physiological principles, the results obtained should also be credible (provided that model design and implementation have been done correctly). In this respect, three issues exist:

1. How meaningful are the equations used? Are they a mathematical form of a well-known physiological principle?
2. How accurate are the equations in describing the data they are based on?
3. Has the model been appropriately designed and implemented?

When can such a mathematical model be useful? Consider an example. In a particular patient with severe adult respiratory distress syndrome (ARDS) and resulting severe hypoxemia, clinicians might be interested in knowing, how extracorporeal membrane oxygenation (ECMO) could improve oxygenation. From pulmonary artery catheterization and arterial blood samples one can obtain the following important oxygen modeling data:

- hemoglobin concentration
- cardiac output
- P50 on dissociation curve
- arterial and mixed venous Arterial Blood Gas (ABG) data

Based on a model constructed for that time point, one could explore the effect of augmenting cardiac output and/or mixed venous oxygen tension in an ECMO situation. Without a model to describe this problem, the best we can do is fit empirical curves to experimental data. However, with a model one can easily ask "what-if" questions: for example, what happens when the ratio of pump oxygenator flow to cardiac output is set at a particular value.¹⁵

Another example of modeling utility, this time from respiratory physiology is: How does a patient's alveolar-arterial oxygen tension difference change with reduced inspired oxygen tensions. The first attempt in answering this question¹⁶ used pulse oximetry.

metry to infer arterial oxygen tension in volunteers subjected to controlled hypoxia by rebreathing. A subsequent study¹⁷ took a more direct approach by cannulating the radial artery of elderly respiratory patient volunteers and drawing off serial arterial blood samples as the patients were subjected to hypoxemia in a hypobaric chamber. This latter study is sufficiently invasive (and even, perhaps, sufficiently risky) that many hospital ethics committees would not approve it under existing guidelines. By contrast, the model-building approach can (and does) provide insight to the problem, and predicts that the alveolar-arterial tension gradient decreases with amplitude.¹⁸⁻²⁰

Pharmacologic modeling is similar to physiological modeling in a great number of respects. All that is required is that the relevant equations be known (see Appendix) and that a means exists to solve and display them.

Simulation in Anesthesia and Critical Care Medicine

Computer simulation methods are potentially useful for training anesthesiologists and for quality assessment programs. In particular, crisis simulation offers a "safe" environment to study individuals' responses to anesthetic errors, equipment failure, critical incidences and other unplanned incidents. Also, adherence to practice standards and guidelines can be studied during simulated crises.

One of the first attempts at electronic simulation in anesthesiology was the SIM-1 system.²¹ Although technically sophisticated for the time (late 1960s), it was not satisfactory for serious clinical training, and simulation technology in anesthesia would wait another three decades for the required computer technology to come to the stage. With the development of high-performance microcomputer technology a number of developments in anesthesia simulation became practical.

CAE/Eagle/MedSim Simulator

The Virtual Anesthesiology Training Simulation System from CAE/Eagle/MedSim (the name reflects a series of corporate sales and takeovers) is a modern anesthesiology simulator conceived for a number of training applications, such as to train anesthesiology residents, for practice with new technology or instruments, for rehearsing anesthetic emergencies, and possibly for future testing, certification, or recertification of anesthesiologists.²²⁻²⁵ It is also of potential use outside the operating room, in such situations as Critical Care Training, Emergency Room Training,

Advanced Cardiac Life Support Training, and the training of physicians or nurses with new monitoring equipment.

The system is composed of a mannequin, associated attachments and computer hardware and software to drive human-like behavior by the mannequin and to simulate various anaesthetic catastrophes. The mannequin includes an anatomically correct head and neck assembly that allows the trainee to intubate the larynx. The lungs can breath spontaneously or passively by hand or mechanical ventilation. Anatomically located loudspeakers in the chest provide heart sounds and breath sounds that can be detected in the usual chest locations with a stethoscope. Servo-controllable lungs "produce" carbon dioxide using a computer-controlled gas metering system. The airway anatomy is such that endobronchial or esophageal intubation is possible. Palpable pulses at the carotid artery and radial artery are also present using real-time simulation. Sites in the mannequin's arm into which intravenous lines can be inserted and drugs infused also exist, although no means to determine automatically what drug or dose was given exists. A simulated twitch response in one of the mannequin's thumbs can be used for the assessment of neuromuscular blockade. Table 3 outlines the system's many capabilities.

The mannequin interfaces with anesthesia machines, respiratory gas analysis devices (capnograph, agent analyzer), pulse oximeters, and other patient monitoring equipment. It is intended to drive all commercially available monitors without modifying setups used in routine clinical care. In all, the following outputs are provided: ECG, arterial pressure, central venous pressure, pulmonary artery pressure, temperature, and pulse oximetry (both waveform and percent saturation). In addition, radial and carotid pulses, as well as non-invasive blood pressure measurements, are available using computer-controlled hydraulics. Many simulated events can be introduced by the operator, including anaphylaxis, aspiration, hemorrhage, malignant hyperthermia, coronary artery constriction, and vagally-mediated bradycardia.

In the respiratory system, events such as pneumothorax, endobronchial intubation, bronchospasm, esophageal intubation and the use of hypoxic gas mixtures can be simulated, with appropriate changes being made on the monitor (e.g., desaturation, hypotension). Cardiovascular events include anaphylaxis, cardiac arrest, hypotension, hypertension, ST segment changes in the electrocardiogram etc. Metabolic events handled include acidosis, diabetic ketoacidosis, hyperkalemia, hypokalemia, malignant hy-

Table 3 - Synopsis of CAE/Eagle/Medsim System Capabilities (adapted from corporate documentation)**(A) Anatomy and physiology**

Receives positive-pressure ventilation
 Performs spontaneous respiration
 Anatomically correct airway, allowing intubation
 Can simulate bronchospasm and unilateral ventilation
 Carbon dioxide production under computer linkage
 Drugs can be injected into the mannequin, and can even be automatically "sensed"

(C) Drug modelling

Models for most real-world anaesthetic drugs:
 - pharmacokinetic (concentration vs time)
 - pharmacodynamic (effect vs concentration)
 Bolus or infusion methods of administration
 Side effects considered in the models

(E) Cardiovascular event simulation

Anaphylaxis
 Sinus bradycardia
 Cardiac arrest
 Hypovolaemia
 Myocardial infarction
 Pericardial tamponade
 ST segment changes
 Supraventricular tachycardia
 Venous air embolism
 Ventricular arrhythmias

(G) Metabolic event simulation

Respiratory acidosis
 Metabolic acidosis
 Malignant hyperthermia reaction
 Hypoglycemia
 Addisonian crisis
 Transfusion reaction

(B) Signals produced

Electrocardiogram
 Capnogram
 Noninvasive BP
 Invasive pressures
 - arterial line
 - CVP
 - PA pressure
 Pulse oximeter signal
 Cardiac output
 Temperature

(D) Clinical signs

Normal breath sounds
 Unilateral breath sounds
 Heart Sounds
 Palpable carotid and radial pulses
 Patient temperature (electronic)
 Thumb twitch from nerve stimulator

(F) Pulmonary event simulation

Endobronchial intubation
 Esophageal intubation
 Pneumothorax
 Pulmonary edema
 Pulmonary embolism
 Bronchospasm
 Hypoxemia

hyperthermia, and transfusion reactions. In addition there are drug effect models which simulate the effects of about 70 intravenous medications on the cardiovascular or pulmonary system. For example, in

response to an induction dose of thiopental, the mannequin will cease to breathe spontaneously and blood pressure and heart rate will change according to the

patient's preoperative hemodynamic status and volume.

I expect that this technology will help considerably to reduce the risk of mistakes due to clinical inexperience. However, it also raises some interesting questions. How realistic are the algorithms on which the simulations are based? Who should cover the costs of running the simulator? Should a trial run at the simulator be part of the final examination process in order to graduate as a physician or for certification as a specialist? What role should this technology play in the formal evaluation of physicians who have been identified as "dangerous"?

One final issue is how to provide feedback to students testing out under the simulator. If a student performs poorly, there are a number of approaches to dealing with the problem without excessively "bruising" the student. Some authorities recommend that your "patient" should not be allowed to be brought to "death" because it may be emotionally traumatic to fail so profoundly. Similarly, in the world of aviation simulation, there is an issue about the wisdom of running pilot simulations under such extreme conditions that a crash would be inevitable.

Software Only Simulation

Software only simulation has many advantages, especially with regard to portability and low cost, and has been used for some time in general medical education. For instance, the Diagnostic Reasoning Cases (DxR cases) software system is a practice based learning package that allows medical students to take a history, examine a virtual patient, order laboratory investigations, and generate clinical hypotheses in the course of diagnosing an actual clinical problem. (See <http://medweb.usc.edu/dxr/index.htm> for some DxR demonstration cases.)

Similarly, the National Board of Medical Examiners (www.nbme.org) has introduced the Computer-based Case Simulations (CCS) examination, formerly known as the CBX (computer-based case simulations) examination, in order to provide a simulated patient experience requiring examinees to continually monitor the patient and make appropriate management decisions.

Several companies offer software-only packages for medical simulation in CD-ROM format. For instance, the Anesoft Corp. (www.anesoft.com) offers anesthesia and critical care software simulation software that are not only educational, but (in my opinion) actually fun to use. These packages were devel-

oped at the University of Washington Department of Anesthesiology. Three programs for Windows and Macintosh systems are available; the best-known is called Anesthesia Simulator and at the time of writing was in its third release. Critical incidents supported in this program include anaphylaxis, cardiac arrest, latex allergy, pneumothorax, renal failure and much more.

The Anesoft ACLS simulation package is an interactive teaching and testing program that contains algorithms, medications, and dosages from the American Heart Association Textbook of Advanced Cardiac Life Support. One is required to interpret electrocardiogram traces, defibrillate, intubate and so on. The 28 simulated cases presented in the package cover asystole, ventricular fibrillation, ventricular tachycardia, atrial fibrillation, atrial flutter, pulseless electrical activity, heart blocks and more. An expert system included in the package for teacher management in shows you what went wrong and what to do next. It can even take over the case for you if you get tired or frustrated. Finally the system provides tutorials on rhythm recognition and treatment as well as tutorials on cardiac medications.

The third package, Critical Care Simulator, offers 20 different critically ill patients for whom one must manage the airway, ventilation, fluids, and drugs to improve the patient's condition.

Mad Scientist Software (<http://www.madsci.com/>) is a company that also offers a number of medical simulation packages such as their Trauma One! teaching package. Gas Man⁵ is another software-only simulation package concerned with anesthetic gases. It is intended to be used as a tool for teaching, simulating and experimenting with anesthetic gas uptake and distribution. The Gas Man computer model graphically simulates the pharmacokinetics of anesthesia administration, showing the time course of gas uptake in each compartment of the body - lungs, heart, brain - as well in as the breathing circuit and vaporizer. It is available from Gas Man Software (<http://www.gasmanweb.com>). Finally, a free simulation of the anesthesia machine has been produced in Web format by the University of Florida.²⁶ It is available online at www.anest.ufl.edu/~eduweb/vam/.

Simulation in Clinical Airway Management

In recent years, clinical airway management has become a focus of simulation technology. Two areas of effort are involved. The first is to develop computer-based models of fluid dynamics to describe gas

flow in the tracheo-bronchial tree; this field, while important, is of limited interest to clinicians.

The other field of airway simulation is more clinical, and focuses on training clinicians. The goal here is simply to produce an instrumented mannequin that can be used in training and performance evaluation. The Laerdal Corporation is the best known in this regard. Its capabilities are listed in Table 4.

Simulation in Regional Anesthesia

Regional anesthesia is a technique which is frequently performed to avoid the need to perform general anesthesia on a patient. One particularly common regional anesthesia technique is epidural anesthesia, a technique that is popular both for childbirth as well as for lower extremity surgery. Recent research efforts have been directed towards simulating this and other regional anesthesia procedures.

than an actual simulation, it covers the topic of regional anesthesia rather comprehensively.

The Biomedical Applications Research Group at the Ohio Supercomputer Center (OSC) (<http://www.osc.edu/>) has for some time been interested in high performance computing applications. One application they have focused on is entitled "Virtual Simulation of Regional Anesthesia" and is intended to help train anesthesiologists in learning epidural anesthesia and other forms of regional anesthesia. The following project description, summarized from their Web site, explains their goals.

"Epidural analgesia is one of the most frequently used techniques for the relief of pain during surgery. In most hospitals with an obstetric anesthesia service, epidural analgesia is the most prominently used anesthesia technique for vaginal childbirth and cesarean section. The procedure involves the injection of a local anesthetic or

Table 4 – Features of the Laerdal Airway Simulator (adapted from the manufacturer's literature)

- Realistic life-size intubation head.
- Bronchial tree is anatomically accurate in size, color and texture and features the accurate anatomical landmarks necessary to facilitate realistic fiberoptic bronchoscopy.
- Standard ALS airway skills are supported:
 - Bag/Valve Mask ventilation
 - Oropharyngeal and nasopharyngeal airway placement
 - Endotracheal tube intubation.
 - Fiberoptic, light wand and retrograde intubation
 - Combitube, LMA placement
 - Trans-tracheal jet ventilation
 - Needle and surgical cricothyrotomy
- Spontaneous respiration with variable respiratory rate, auscultation of breath sounds and CO₂ detection.
- Airway complications: pharyngeal obstruction, tongue edema, trismus, laryngospasm, decreased cervical range of motion, decreased lung compliance, stomach distension, pneumothorax decompression.
- Cannot-Intubate-Can-Ventilate or Cannot-Intubate-Cannot Ventilate conditions

Regional ABC is a hands-on, Web-based regional anesthesia guide from Duke University Medical Center. It focuses on regional anesthesia of the lower extremity and may be viewed at <http://anesthesia.mc.duke.edu/regional/abc/index.html>. It is intended both as an educational tool and a patient care resource. Much of the information on this site can be exported to handheld computers for use at the patient bedside. Blocks described include: (1) Lumbar plexus: Femoral nerve, Genitofemoral nerve, Ilioinguinal nerve / Iliohypogastric nerve, Lateral Femoral Cutaneous nerve, Obturator nerve, Spinal nerve (2) Sacral plexus: Sciatic nerve, Posterior Femoral Cutaneous nerve, Gluteal region block. While the site is more instructional/informational

opioid into the epidural space of the spinal column. Although a single degree-of-freedom task, it is a delicate manual operation that requires the placement of a catheter into the epidural space using only haptic cues to guide the needle. By feeling the resistive forces of the needle passing through the various tissues, the anesthesiologist must maneuver the tip of the needle into the correct space without perforating and damaging the spinal cord in the process. Limitations of physical models such as mannequins include lack of patient variance, inaccurate representation of biological tissue, and physical wear from repeated use. The use of cadaveric material offers limited opportunities and associated risks. The

best method of training residents on this delicate and dangerous manual task remains the use of live patients, a scenario obviously not optimal for patients. In addition, teaching this technique requires highly intensive tutorial interaction with faculty due to the significant learning curve in understanding exact placement of the needle. This ongoing collaborative effort between researchers at The Ohio State University Hospitals, Immersion Corporation, and OSC is to create and test a virtual simulator for training residents in the use of regional anesthesiology. Under funding from the Department of Defense, we are creating a system for teaching a specific method of regional anesthesia, the epidural technique. Our methods include the application and integration of virtual technologies. Our system components include a high-performance graphics workstation capable of stereo display, a real-time volume renderer, a voice-activated interface, and a one-dimensional haptic probe capable of simulating the resistive forces of penetrated tissues. The system will enable the resident to investigate various three-dimensional reconstructed data sets in a nonthreatening environment. The system can be cued through voice activation to provide additional information in text, audio, or graphical form. Furthermore, the system incorporates the necessary components to allow the resident to "feel" the technique as performed by the expert. By providing a new form of procedural training in a nonthreatening environment, the simulator will increase the proficiency level of the resident in technique delivery and improve competency required for live human trials. "

Kirkpatrick's "Four Levels of Evaluation" Applied to Medical Simulation

Evaluation of teaching programs and other initiatives is important to determine if effort and money has been spent wisely. One well-known approach to program evaluation is Kirkpatrick's "Four Levels of Evaluation", first developed in 1959. At the time, Donald Kirkpatrick was a professor of marketing at the University of Wisconsin. His four levels of evaluation involve four kinds of measurement:

Level 1: Reaction – measurement of satisfaction

Level 2: Learning - measurement of learning

Level 3: Behavior - measurement of behavior change

Level 4: Results - measurement of results

Questions associated with each level that guide the measurements are as follows:

Level 1: (Reaction) Were the participants pleased with the program? How would they rate their experience? What suggestions can be made to improve the experience?

Level 2: (Learning) What skills, knowledge, insights or attitudes have changed from the program?

Level 3: (Behavior) Did the participants change their behavior based on what was presented in the program?

Level 4: (Results) Did the change in behavior positively affect the organization or influence an objective outcome?

Although this particular paradigm is popular in the worlds of business and education, it is less well-known in clinical circles, so that few specific evaluations of medical simulations programs in this particular context have been made. However, a number of related studies have been undertaken to address related issues.

In a study carried out at the University of Toronto²⁷ the authors "wished to determine whether a simulator-based evaluation technique assessing clinical performance could demonstrate construct validity and determine the subjects' perception of realism of the evaluation process." The simulation involved preoperative patient evaluation, anesthesia induction, and maintenance of anesthesia. Each problem presented to the subject as part of the simulation in a structured manner; examples of problems included atelectasis, coronary ischemia, and hypothermia. After the simulation, participants rated the realism of their experience on a 10-point visual analog scale (VAS). The overall realism VAS score was 7.8. The subjects rated the realism of the test scenario highly (Kirkpatrick level 1), but the other levels were not explicitly examined.

In a study at the University of Washington²⁸ investigators sought "to determine whether an advanced cardiac life support (ACLS) computer simulation program improves retention of ACLS guidelines more effectively than textbook review." Using a randomized, controlled trial in an academic medical center, forty-five anesthesia residents and faculty were tested 10 to 11 months after ACLS provider course training. Participants were randomized to textbook or simulator training and asked to prepare for a mock resuscitation (Mega Code). The examination sessions

were videotaped and scored; participants who used the ACLS simulation program scored significantly higher than participants who reviewed using a textbook . The authors concluded that “use of a computerized ACLS simulation program improves retention of ACLS guidelines better than textbook review.” This was a study which focused on Kirkpatrick’s level 2.

Another simulator study carried out at the University of Washington²⁹ sought to measure the effec-

tiveness of screen-based simulator training with debriefing on the response to simulated anesthetic critical incidents using a mannequin-based simulator. Thirty-one anesthesia residents were randomized into two groups. Their approach examined Kirkpatrick’s levels 2 and 3. The intervention group was presented with ten anesthetic emergencies using the screen-based anesthesia simulator program and received written feedback on their management, whereas the control group was asked to study a handout covering the same ten emergencies. All residents were then

Table 5 -- Research Issues That Can Be Addressed Using Anesthesia Simulators

Modified from Table 80-7, Miller’s Textbook of Anesthesia, 5th Edition.

Cognitive science of dynamic decision-making
What is the interaction of precompiled procedural knowledge versus deep medical knowledge and abstract reasoning?
How does supervisory control of observation relate to vigilance, data overload, and visual scanning patterns?
What is the information content of watching the surgical field?
How are optimum action planning and scheduling implemented?
How does reevaluation fail, resulting in fixation errors?
Human-machine interactions
What is the distraction penalty of false alarms?
Is there an advantage to integrated monitors and displays versus multiple stand-alone devices and displays?
How easy to use are the controls and displays of existing anesthesia equipment in standard case situations and in crisis situations? Do they invite mode errors?
What is the mental workload imposed by a new diagnostic device such as transesophageal echocardiography?
Teaching anesthesia in the operating room
How much teaching can be accomplished in the operating room without sacrificing the anesthesia crew's vigilance?
How well can faculty detect and categorize the performance of anesthesia trainees?
What teaching styles are best integrated with case management in the operating room?
Teamwork
How does the anesthesia crew interact during case and crisis management? How is workload distributed among individuals? How do crew members communicate with each other, and how do they communicate with other members of the operating room team?
Effects of performance-shaping factors on anesthetist performance
How do sleep deprivation, fatigue, aging, or the carryover effects of over-the-counter medications, coffee, or alcohol affect the performance of anesthetists?
Intelligent decision support
Can smart alarm systems or artificial intelligence provide correct and clinically meaningful decision support in the operating room or intensive care unit?

evaluated on their management of 4 standardized scenarios in a mannequin-based simulator. The authors found that “residents who managed anesthetic problems using a screen-based anesthesia simulator handled the emergencies in a mannequin-based anesthesia simulator better than residents who were asked to study a handout covering the same problems” and they concluded that “computer simulations with feedback are effective as a supplement to traditional residency training methods for the management of medical emergencies.”

Research Issues

Simulation can be used as a powerful tool for studying human performance issues (training, teamwork, fatigue) as well as for exploring human-machine interactions, and for the studying design flaws in medical equipment. Table 5 lists some of the many research issues in this area. Note that many of these issues center on situational awareness and clinical crisis management and draw on experience developed in the aviation industry.

Conclusion

Although computer-based simulation in anesthesiology and critical care medicine is in its early years, already much has been accomplished. Applications range from scientific modeling to clinical performance appraisal in the setting of crisis management. Still, much remains to be done to demonstrate its scientific and clinical utility, especially in the context of the Fitzpatrick model.

Disclaimer

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Correspondence

Dr. D. John Doyle
Department of General Anesthesiology
Cleveland Clinic Foundation – E31
9500 Euclid Avenue
Cleveland, Ohio, 44195
USA

216-444-1927 (Voice)
216-444-2200 Pager 29456
216-444-9247 (Fax)

E-mail doylej@ccf.org

Appendix

Pharmacokinetics in a Nutshell

In simple technical terms, pharmacokinetic modeling is playing with first order linear differential equations. The simplest model, involving only a central compartment which the drug enters, is summarized in equation format below.

Key equations of pharmacokinetics (one compartment model)

1. Volume of Distribution = $\frac{\text{Drug Dose}}{\text{Plasma Concentration (at time 0)}}$
2. Plasma Drug Clearance = Volume of Distribution x Elimination Rate Constant
3. Drug Half-Life = $\frac{0.693}{\text{Elimination Rate Constant}}$

Key equations of pharmacokinetics expressed in abbreviated form

1. $V_D = \frac{D}{C_o}$
2. $Cl = V_D \times K_e$
3. $t_{1/2} = \frac{0.693}{K_e}$
4. $V_D = \frac{Cl}{K_e} = \frac{Cl \times t_{1/2}}{0.693}$

Abbreviations

- C_o Plasma Concentration (at time 0)
- Cl Plasma Drug Clearance
- D Drug Dose
- K_e Elimination Rate Constant
- $t_{1/2}$ Drug Half-Life

The equations describing the dynamics of plasma drug concentration for the various types of compartmental models are given below. The more sophisticated three-compartment model (one central compartment and two peripheral compartments) does a much better job of matching experimental observations, accounting for its popularity in serious pharmacokinetic studies.

Essential Equations to do Pharmacokinetic Modeling

C_p = plasma concentration of drug in central compartment.

1. One compartment model: $C_p = C_0 e^{-K_e t}$
2. Two compartment model: $C_p = A e^{-at} + B e^{-bt}$
3. Three compartment model: $C_p = A e^{-at} + B e^{-bt} + C e^{-ct}$

Parameters Needed to do Pharmacokinetic Modeling

1. One compartment: C_0, K_e
2. Two compartment: A, B, a, b
3. Three compartment A, B, C, a, b, c

Mathematical Details of the Three Compartment Model

If \mathbf{A}_1 is the amount of drug in compartment 1, and \mathbf{A}_2 and \mathbf{A}_3 apply similarly, then the rate of change of drug concentration in each compartment are expressed by three differential equations (first-order, linear and coupled, for the technical types reading this).

$$d\mathbf{A}_1/dt = \mathbf{R} + \mathbf{K}_{21}\mathbf{A}_2 + \mathbf{K}_{31}\mathbf{A}_3 - (\mathbf{K}_e + \mathbf{K}_{12} + \mathbf{K}_{13}) \mathbf{A}_1$$

$$d\mathbf{A}_2/dt = \mathbf{K}_{12}\mathbf{A}_1 - \mathbf{K}_{21}\mathbf{A}_2$$

$$d\mathbf{A}_3/dt = \mathbf{K}_{13}\mathbf{A}_1 - \mathbf{K}_{31}\mathbf{A}_3$$

\mathbf{R} = drug infusion rate into central compartment (scalar quantity)

\mathbf{A}_i = drug amount in compartment i (3×1 matrix)

\mathbf{K}_{ij} = intercompartmental transfer coefficient matrix (3×3 matrix)

There is no simple solution to this set of equations. Analytical solutions have been published, but it is not especially difficult to solve the equations numerically, for example, using Euler's method [Maitre PO, Shafer SL. A simple pocket calculator approach to predict anesthetic drug concentrations from pharmacokinetic data. *Anesthesiology*. 1990; 73:332-6].

However, these equations govern the mass (amount) of drug in each compartment; to go from drug mass to drug concentration one must divide the mass by the volume the drug is dissolved in, or "volume of distribution". Since generally we are only interested in drug concentration in the central compartment (compartment 1), only the volume of distribution for the central compartment (V_1) is of interest to most pharmacokineticists.

Thus, you need to know seven things to develop a three-compartment pharmacokinetic model: R , V_1 , K_e , K_{12} , K_{21} , K_{13} , and K_{31} . (Actually, you also need to know some initial condition data about the drugs on board at time zero, but we generally set all that to zero.)

Given these seven parameters [which are not always easy to obtain in the real world] one can predict the drug concentration that might be expected in an "average" patient for a given pattern of drug delivery into the patient's IV. The prediction is based on average pharmacokinetic data from study patients; specific pharmacokinetic data for a particular patient is unlikely to ever be clinically practical. Your patient may vary very much from the "average" if, for example, he or she is in renal failure or is quite elderly. Other influences might be expected in patients taking other drugs concurrently (e.g. cimetidine) or with pharmacokinetic disorders (e.g. atypical plasma cholinesterase). Thus, a particular set of PK parameters has meaning only for the group they were obtained for, usually not-so-elderly patients with good hepatic and renal function taking minimal concurrent medication.

Some older reports use simpler 2 or 1 compartment models to describe pharmacokinetic behavior. For a 2 compartment model, let $K_{13} = K_{31} = 0$. For a 1-compartment model, in addition, let $K_{12} = K_{21} = 0$. This gives us the simplest pharmacokinetic model - a one-compartment model; here, the drug entering mixes instantly in the central compartment and is eliminated according to the elimination rate constant K_e :

$$dA / dt = R - K_e A$$