Respiratory System Simulations and Modeling

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Simulators and models of the respiratory system range from simple mechanical devices to complex systems that include sophisticated computers. These systems have considerable utility in clinician education, guiding therapies, evaluating new devices and techniques, and in improving our understanding of the cardiorespiratory system. Simulators and models are of 3 types: signs-and-symptoms simulators, anatomic models, and physiologic models. Signs-and-symptoms simulators range from human actors to computer-controlled patient mannequins. Clinical scenarios, from minor abnormalities to catastrophic emergencies, can be simulated. As has been found with aircraft cockpit simulators, improved clinician performance in simulated emergencies should translate into improved performance in real patient-care situations. Anatomic modeling can simulate basic anatomy for training clinicians. Three-dimensional reconstruction of the airways, using real patient data, can help to plan therapy, understand the disease process, and warn of safety issues. Anatomic modeling with radiographs and magnetic resonance images, sometimes created using radiolabeled tracer gases, can create 3-dimensional images of regional lung anatomy and function. Physiologic signals such as carbon dioxide production, oxygen consumption, and washout/washin of various tracer gases can be used to model ventilation-perfusion and ventilation-volume relationships, and those models can improve understanding of disease processes and guide therapies. *Key words: computer simulation; respiratory system; models, theoretical; models, anatomical.*
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Introduction

Simulations and modeling in respiratory medicine offer a number of opportunities. First, models and simulations can give us better understanding of the pathophysiology of disease processes. For example, constructing a multi-unit lung model with different regional ventilation and perfusion properties can help us understand gas exchange disturbances.[1] Second, simulations and models are powerful educational tools.[2] Observing a simulator or model's re-

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sponse to various manipulations can help educate health care professionals in diagnosis and treatment decisions. Indeed, a wrong decision on an education simulator leads only to clinician learning, not to a real patient disaster. Education simulators can also be used for clinician testing and licensing. Third, a simulator or model can help predict a patient's response to planned therapies. For example, a mechanical lung model may be able to predict how a patient's respiratory system will respond to a change in a ventilator setting or how a vasodilator drug might affect gas exchange.[3] Fourth, a computerized anatomic model of the respiratory system can be used to diagnose anatomic lesions and guide bronchoscopy and other invasive techniques.[4] Fifth, simulators and models help assess and improve existing and new ventilation devices, techniques, and modes.

Approaches to modeling or simulating the respiratory system have taken many forms over the years. A long-standing example is the use of actors to feign various disease symptoms and thus help teach students how to elicit a medical history. Mathematical modeling of various respiratory gas behaviors has also been used throughout the past century to construct multi-unit lung models for describing ventilation and gas exchange. Improvements in programming and computing power have increased the potential for modeling and simulating the respiratory system. Sophisticated interactive text/video programs are now available to simulate medical conditions, for both teaching and testing. Patient signs and symptoms can be simulated with considerable detail on computer-driven mannequins. Complex analyses of radiographic images can be used to create detailed anatomic models for teaching, diagnosis, and guiding therapy. And sophisticated analyses of certain physiologic signals can be used to create anatomic and physiologic models of respiratory system behavior.

This report describes 3 uses of computer simulations and modeling of the respiratory system: (1) computer-driven models and simulators of patient signs and symptoms, (2) anatomic modeling of the lung, either from anatomic principles or from imaging techniques, and (3) physiologic simulation and modeling by analyzing various physiologic gas behaviors.

Computerized Simulation of Patient Signs and Symptoms

Simulating patient signs and symptoms can be done in 3 different ways. The simplest is to have computerized text and figures show signs and symptoms. These can be integrated with questions and answers about diagnosis and treatment. A more sophisticated approach would allow for different user decisions to lead to different simulated clinical responses. Computer graphics can also be used to visually simulate patient signs and symptoms, and these can be incorporated with laboratory data, radiographic images, and other physiologic data. Applications include not only student instruction but also testing, certification, and licensure. The most sophisticated signs-and-symptoms simulator is the computer-driven mannequin ("human patient simulator"),[5] a life-size human mannequin capable of simulating many physiologic functions. The mannequin's multiple functions are computer-controlled, programmable, and respond to user decisions/actions. The human patient simulator has realistic chest movements, breath sounds, pupil sizes, skin color, airway anatomy (normal and pathologic), and thoracostomy insertion sites. Various monitors and life-support systems (eg, ventilators) are also available and can be operated by the user. Table 1 lists respiratory system variables and clinical scenarios that can be realistically simulated with the device.

Table 1. Adjustable Respiratory Variables on a Computerized "Human Patient Simulator"

Upper Airway, Trachea, and Main Bronchus
Anatomy
Tracheal occlusion: total or partial
Bronchial occlusion: right vs left
Laryngospasm
Swollen tongue
Breath Sounds
Normal
Muffled
Wheezing
Rales
Volume in right vs left
Respiratory System Mechanics
Lung compliance
Chest wall compliance
Airway resistance
Functional residual capacity
Pneumothorax (including chest tube function)
Gas Exchange
Shunt fraction
Dead space
Oxygen consumption
Carbon dioxide production

(Adapted from Reference 5.)

The human patient simulator is usually set up in a dedicated suite with cameras to record the user's activities, review of which can provide valuable insight. The video and the simulator data can also be transmitted to classrooms at distant locations.

The most widely used application of these signs and symptoms simulators is clinician training and testing. Several licensing boards, including the National Board for Respiratory Care, use simple text simulations on computer screens. More sophisticated computer-based video simulations effectively improve test and performance capabilities in neonatal resuscitation, radiology suite emergencies, cardiopulmonary resuscitation, and advanced cardiac and trauma life support.[6–8] Two historically controlled studies suggested that rapid-response teams formally trained with video simulation methods can reduce hospital mortality.[9,10]

The growing availability of human patient simulators and similar systems offers the opportunity for more comprehensive and realistic training and testing. For example, such systems can help teach and evaluate a student's integration of assessment, judgment, and physical skills in respiratory emergencies such as pneumothorax, bronchospasm, or difficult airway intubation in a realistic clinical environment.

Human-patient-simulator systems for training and testing have been most extensively evaluated in the anesthesia literature.[11–15] This has been driven by efforts to reduce anesthesia mishaps and to lower anesthesia malpractice rates.[16] Analogies have been drawn to aircraft cockpit simulators, which have been shown to improve pilot performance in various emergency circumstances.[17,18]

Human-patient-simulator system outcomes have been assessed primarily as performance improvement under simulator conditions.[19–23] Positive trainee feedback has also been cited as a valid outcome.[22,23] Unfortunately, there are no outcome data that prove that human-patient-simulator training actually reduces anesthesia (or other medical) complications, but that would seem to be a logical extrapolation.[24,25]

Another application of signs and symptoms simulators is to assess the accuracy and reliability of monitoring systems (eg, exhaled gas analyzers, respiratory pattern analyzers, and ventilator alarm systems) and test monitoring systems' automated responses.[26]

Computerized Anatomic Simulation and Modeling of the Respiratory System

Simulating the Airways

There are 2 basic applications of computerized simulation and modeling of the airways. The first is computer-generated simulation of bronchoscopy for teaching. The second is reconstruction of radiographs to create 3-dimensional pictures of the airway for diagnosis and treatment.

Computerized bronchoscopy creates a video simulation of the tracheobronchial tree, which can interact with a bronchoscopy device operated by the trainee.[27] The bronchoscope is inserted into a computerized sensing device that recognizes the position of the bronchoscope and the various instruments inserted through it. The visual image and the motion of the bronchoscope and instruments appear on a computer screen. Normal anatomical structures, complications (eg, hemorrhage), and pathologies (eg, tumors) can all be simulated. Moreover, the simulated abnormalities can be treated (eg, lavaged or biopsied) with the simulated instruments. This device can be very effective both for initial training of bronchoscopists and for refresher training for bronchoscopic emergencies such as hemorrhage and pneumothorax.

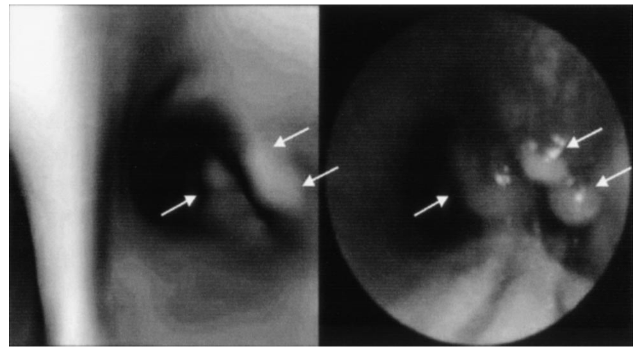

Fig. 1. Virtual bronchoscopy. On the left is a 3-dimensional image of the airway lumen, constructed from computed tomography images. On the right is an actual bronchoscopy image of the same location. The arrows point to airway lesions. (From Reference 28, with permission.)

The second approach to anatomic simulation of the airways, sometimes called "virtual bronchoscopy," involves reconstruction of computed tomography (CT) data to create 3-dimensional images of the airways.[4,28] Airway abnormalities such as tumors, stenotic areas, and strictures can be depicted (Fig. 1), which assists in assessment and planning for interventions such as biopsies, stents, laser resections, and medication targeting (eg, brachytherapy). It also allows the bronchoscopist to see what might be distal to the lesion.

A novel extension of the virtual bronchoscopy concept is to use computers to match CT images to actual bronchoscope location.[29] A very small sensor is placed at the tip of the bronchoscope and an array of sensors is placed around the patient's thorax. The patient's CT scan is loaded into the computer, and the bronchoscope is inserted into the airway and placed at several anatomic locations (eg, carina, bifurcations of various lobes). The external detectors then plot the sensor location on corresponding locations on the CT scan (Fig. 2). In essence this allows the bronchoscopist to guide the bronchoscope via the CT images. Peripheral lesions can be more accurately located and various diagnostic and therapeutic procedures performed.

Parenchymal and Mediastinal Modeling and Simulations

The development of CT in the 1970s allowed for 2-dimensional reconstruction of radiographs to produce mul-

Fig. 2. Computerized sensing of bronchoscope location. Pictured are 3 planes of a computed tomography image of a patient with a lesion in the left upper lobe. The patient lies on a platform that contains sensors that detect the position of the bronchoscope tip (striped rod). That information is superimposed on the CT image, showing the bronchoscope's position with respect to the lesion. (Courtesy of superDimension GmbH, Düsseldorf, Germany.)

tiple axial "slices" through the lung. Viewing the slices sequentially from apex to base allows the interpreter to construct in his/her mind a 3-dimensional image. In the 1990s computer analysis of magnetic resonance signals allowed similar types of imaging constructs. Magnetic resonance images (MRIs) have considerable potential for obtaining more specific anatomic and physiologic information.[4]

In recent years various contrasting and radiolabeled gases have been used in conjunction with CT and MRI to create more detailed 3-dimensional lung images.[30] For example, hyperpolarized helium can be used to create 3-dimensional images of lung ventilation.[31] This can be very useful for detecting regions that might be amenable to lung-volume-reduction surgery in emphysema patients. Similar techniques that use contrasting or radiolabeled vascular markers can create 3-dimensional images of lung perfusion patterns. Indeed, the diagnosis of pulmonary embolism has been revolutionized by vascular contrasted CT images.[32]

CT and MRI technology could be very useful in the intensive care unit (ICU) to help optimize ventilator settings and guide alveolar recruitment strategies.[33] Currently, there are no CT or MRI devices that can be transported easily to the bedside, but a new technique, electrical impedance tomography, can create a simple cross-sectional image of the lung.[34] In electrical impedance tomography multiple electrocardiograph-like electrodes are placed around the patient's chest. Simultaneous measurement of the electrical impedance between all the electrodes allows creation of a 2-dimensional image that distinguishes aerated lung regions from denser vascular and other soft-tissue structures. The potential thus exists for a portable ICU device that can visualize recruited versus unrecruited lung regions (Fig. 3).

Computerized Physiologic Simulation and Modeling

There are 3 ways that computer analysis of physiologic signals can produce functional simulation and modeling of the respiratory system: by simulating respiratory system mechanics; by simulating the regional distribution of ventilation with respect to lung volume; and by simulating gas

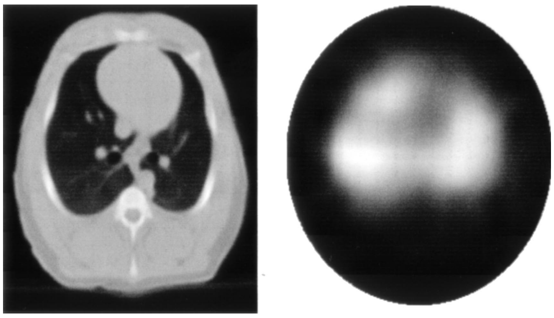

Fig. 3. Conventional computed tomogram (left) versus image created with electrical impedance tomography (EIT). EIT allows intensive-care-unit imaging of the lung, and the EIT image allows identification of atelectatic and aerated lung regions. The images are created in a single cross-sectional plane by computer reconstruction of electrical impedance readings across an array of electrodes wrapped around the chest. The image on the left is a conventional computed tomogram slice and the image on the right is an EIT cross-sectional image of the same slice. The aerated regions on the EIT image are white and the heart shadow is dark. (From Reference 34, with permission.)

exchange behavior in the lung (ie, simulating ventilation/perfusion [$\dot{V}/\dot{Q}$] matching).

Respiratory System Mechanics

The earliest mechanics simulators were simple spring-loaded bellows that simulated the passive respiratory system. Adjusting the spring position or the tubing resistance changed the compliance and resistance. These were later modified with driving mechanisms to simulate an active patient. These approaches have been used for years to teach students about mechanical ventilation operations and to help evaluate novel designs in mechanical ventilation. The basic principle of these mechanical models was to utilize the simplified equation of motion:

$$\text{Driving pressure} = (\text{volume/compliance}) + (\text{flow} \times \text{resistance})$$

In an active lung simulator a second driving pressure is created by adding a driving mechanism that simulates patient effort.

Though clearly useful, these mechanical models lack the complexities of real patients. First, mechanical models have only a single compliance; they cannot distinguish between lung compliance and chest-wall compliance. Second, the simulated compliance is linear and does not represent the sigmoidal shape of true respiratory system compliance. Third, the resistance is a single value that does not vary with volume or flow, as it does in a patient. Fourth, intrinsic positive end-expiratory pressure from collapsing airways cannot be easily mechanically simulated.

In the active patient there are further limitations. For example, these simple mechanical models generally either have a simulated constant-flow or a constant-pressure signal, and these simulated demands cannot react to the ventilator. Thus, the complexities of spontaneous ventilatory drive are virtually impossible to simulate with these mechanical devices.

In recent years computers have been added to mechanical models to improve mechanics simulation.[35,36] A computer can simulate regional behavior (although the current generation simplifies the model to a 2-unit system), can create nonlinear compliance and resistance, and can vary the active inspiratory pattern. The more sophisticated of these systems can program changes in certain variables over time, in a scripted educational program. The current generation of devices, however, still has difficulty simulating the physiology of collapsing airways and the variation in flow and patient flow demand that occurs with ventilator flow delivery. Applications for these devices include clinician education/testing and testing new ventilation devices and techniques. These devices can also be used to predict a patient's response to a change in ventilator settings, by programming the patient's mechanics into the device and observing the device's response to changes.[37]

Another approach is a pure computer simulation of the respiratory system and ventilator combined. This approach may provide simulations of airway collapse and changing patient ventilator demand in response to ventilator function. Simplified versions of this are available on some ventilators, both for clinician education and predicting patient response to changes in ventilator settings. At this point, however, simulations of airway collapse and varying patient demand in response to ventilator flow are not available.

Regional Ventilation With Respect to Volume

Regional distribution of inhaled gases can be evaluated by analysis of various physiologic signals. For example, simple analysis of gas-washout curves can be used to construct 2-unit lung models that illustrate ventilation maldistribution.[38,39] Imaging techniques that use radiopaque or radiolabeled aerosols allow more direct visualization of regional ventilation and regional residual volume.[40] Unlike the gas-washout models, which usually can only create a 2-unit model, these visual modeling techniques can produce multiple ventilation distribution units. Indeed, they can be matched with perfusion imaging to create regional images of [$\dot{V}/\dot{Q}$] matching.

Computerized Physiologic Modeling of Gas Exchange

Evaluations of the alveolar-arterial oxygen gradient and alveolar-arterial carbon dioxide gradient allow for simple

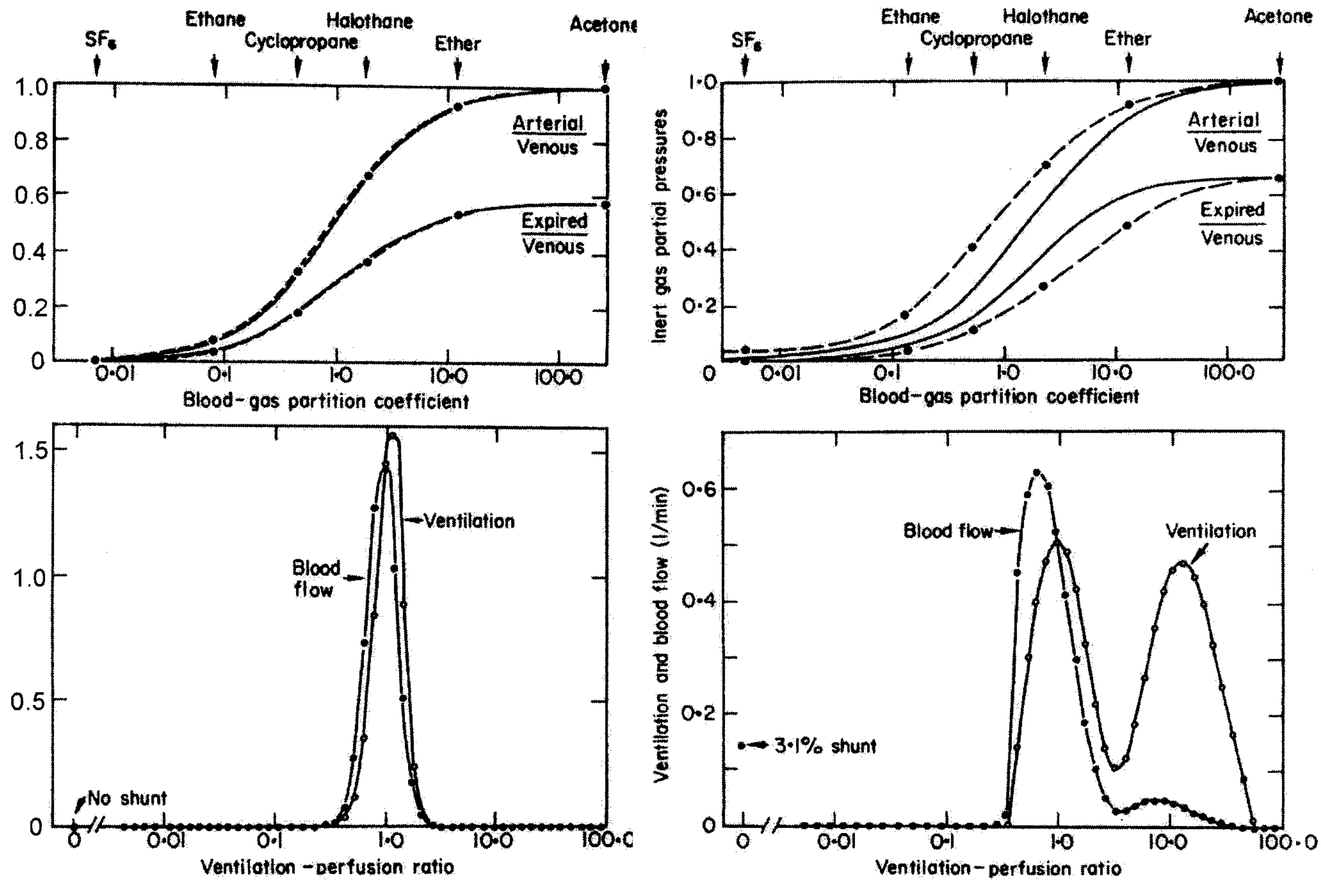

Fig. 4. Curves created with the multiple inert-gas elimination technique (see text). Six gases with different solubilities are administered to the patient and the relative retention/elimination of the gases (upper panels) provides the data for a 50-unit lung model with a wide range of ventilation/perfusion relationships (lower panels). In the example on the left, from a normal subject, almost all of the ventilation and blood flow are going to units that have a ventilation/perfusion relationship that is near 1. In the example on the right, from a subject with vascular disease, considerable ventilation is being "wasted" in high ventilation/perfusion units. (Adapted from Reference 41, with permission.)

modeling of [$\dot{V}/\dot{Q}$] distributions and dead space. A much more sophisticated approach is the multiple inert-gas elimination technique,[41] in which 6 gases of different solubility (sulfur hexafluoride, ethrane, cyclopropane, halothane, ether, and acetone) are inhaled by the patient. Analysis of the exhaled gas determines the extraction versus elimination ratios, which are used to develop a 50-unit lung model of [$\dot{V}/\dot{Q}$] relationships (Fig. 4). The multiple inert-gas elimination technique can be used to assess various therapies, such as vasodilators and changes in ventilator settings.

A simpler approach might be to analyze exhaled carbon monoxide, methane, and acetylene after a single inspiration of those gases.[42] Methane is an inert gas that simply distributes throughout the alveolar gas region. Acetylene is a soluble gas, the absorption of which depends on pulmonary capillary blood flow. And carbon monoxide is a diffusion-limited gas, the uptake of which is primarily determined by pulmonary vascular blood volume and hemoglobin. By analyzing these gases as the lung empties we can create regional models of gas volumes, blood flow, and blood volume in the rapidly-emptying lung regions versus the slower-emptying regions.[43] This approach might help determine ventilator settings or predict patient response to therapies.

Summary

Simulators and models of the respiratory system can assist clinician education, guide therapies, assist in evaluating new devices and techniques, and improve our understanding of the cardiorespiratory system. Signs-and-symptoms simulators have important utility in clinician training and testing. As with aircraft cockpit simulators, improved clinician performance in simulated emergencies should translate into improved performance in real situations.

Anatomic modeling can be used to simulate basic anatomy for training endoscopists and bronchoscopists. Three-dimensional reconstruction of the airway can use real patient data to create models that help to plan therapy, better understand the disease process, and warn of safety issues.

A novel technique also allows for guiding bronchoscopy by superimposing the bronchoscope onto the CT image. Parenchymal anatomic modeling using radiographs or MRIs, especially when created with radiolabeled tracer gases, can create 3-dimensional images of regional anatomy and function.

Finally, physiologic signals from gas production, gas elimination, and washout/washin of various tracer gases allow construction of physiologic models of [$\dot{V}/\dot{Q}$] and ventilation-volume relationships.

These techniques can improve our understanding of respiratory structure and function, enhance clinician education, improve diagnostic capabilities, improve patient safety during procedures, help predict and assess responses to therapy, guide ventilator settings, and aid in developing new devices and improving ventilation techniques.

REFERENCES

1. West JB, Wagner PD. Pulmonary gas exchange. In: West JB, Wagner PD, editors. Bioengineering aspects of the lung. New York: Marcel Dekker: 1977.
2. Gaba DM, Howard SK, Fish KJ, et al. Simulation-based training in anesthesia crisis resource management (ACRM): a decade of experience. Simul Gaming 2001;32:175–193.
3. Graham BL, Dosman JA, Cotton DJ. A theoretical analysis of the single breath diffusing capacity for carbon monoxide. IEEE Trans Biomed Eng 1980;27(4):221–227.
4. Muller NL. Computed tomography and magnetic resonance imaging: past, present and future. Eur Respir J Suppl 2002;35:3s–12s.
5. Meti Corp Web site. Available at: http://www.meti.com. Accessed January 22, 2004.
6. Halamek LP, Kaegi DM, Gaba DM, Sowb YA, Smith BC, Smith BE, Howard SK. Time for a new paradigm in pediatric medical education: teaching neonatal resuscitation in a simulated delivery room environment. Pediatrics 2000;106(4):E45.
7. Sica GT, Barron DM, Blum R, Frenna TH, Raemer DB. Computerized realistic simulation: a teaching module for crisis management in radiology. AJR Am J Roentgenol 1999;172(2):301–304.
8. McLaughlin SA, Doezema D, Sklar DP. Human simulation in emergency medicine training: a model curriculum. Acad Emerg Med 2002;9(11):1310–1318.
9. Buist MD, Moore GE, Bernard SA, Waxman BP, Anderson JN, Nguyen TV. Effects of a medical emergency team on reduction of incidence of and mortality from unexpected cardiac arrests in hospital: Preliminary study. BMJ 2002;324(7334):387–390.
10. Henderson SO, Ballesteros D. Evaluation of a hospital-wide resuscitation team: does it increase survival for in-hospital cardiopulmonary arrest? Resuscitation 2001;48(2):111–116.
11. Chopra V, Gesink BJ, de Jong J, Bovill JG, Spierdijk J, Brand R. Does training on an anaesthesia simulator lead to improvement in performance? Br J Anaesth 1994;73(3):293–297.
12. Gaba DM, DeAnda A. The response of anesthesia trainees to simulated critical incidents. Anesth Analg 1989;68(4):444–451.
13. Howard SK, Gaba DM, Smith BE, Weinger MB, Herndon C, Keshavacharya S, Rosekind MR. Simulation study of rested versus sleep-deprived anesthesiologists. Anesthesiology 2003;98(6):1345–1355.
14. Gaba DM, Howard SK, Flanagan BF, Smith BE, Fish KJ, Botney R. Assessment of clinical performance during simulated crises using both technical and behavioral ratings. Anesthesiology 1998;89(1):8–18.
15. Devitt JH, Kurrek MM, Cohen MM, Fish K, Fish P, Muphy PM, Szalai JP. Testing the raters: inter-rater reliability of standardized anaesthesia simulator performance. Can J Anaesth 1997;44(9):924–928.
16. Bushell E, Gaba D. Anesthesia simulation and patient safety. Prob Anesth 2002;13:506–514.
17. Billings C, Reynard WD. Human factors in aircraft incidents: results of a 7-year study. Aviat Space Environ Med 1984;55(10):960–965.
18. Weiner E, Kanki B, Helmreich R. Cockpit resource management. San Diego: Academic Press: 1993.
19. Gaba DM, DeAnda A. A comprehensive anesthesia simulation environment: re-creating the operating room for research and training. Anesthesiology 1988;69(3):387–394.
20. Taffinder NJ. Better surgical training in shorter hours (editorial). J R Soc Med 1999;92(7):329–331.
21. Forrest F, Taylor M. High level simulators in medical education. Hosp Med 1998;59(8):653–655.
22. O'Brien G, Haughton A, Flanagan B. Interns' perceptions of performance and confidence in participating in and managing simulated and real cardiac arrest situations. Med Teach 2001;23(4):389–395.
23. Lighthall GK, Barr J, Howard SK, Gellar E, Sowb Y, Bertacini E, Gaba D. Use of a fully simulated intensive care unit environment for critical event management training for internal medicine residents. Crit Care Med 2003;31(10):2437–2443.
24. Kurrek MM, Fish KJ. Anaesthesia crisis resource management training: an intimidating concept, a rewarding experience. Can J Anaesth 1996;43(5 Pt 1):430–434.
25. DeAnda A, Gaba DM. Unplanned incidents during comprehensive anesthesia simulation. Anaesth Analg 1990;71(1):77–82.
26. Larsson JE, Hayes-Roth B, Gaba DM, Smith BE. Evaluation of a medical diagnosis system using simulator test scenarios. Artif Intell Med 1997;11(2):119–140.
27. Immersion Medical Web site: Available at: http://www.immersion.com. Accessed January 22, 2004.
28. Haponik EF, Aquino SL, Vining DJ. Virtual bronchoscopy. Clin Chest Med 1999;20(1):201–217.
29. Superdimension Web site: Available at: http://www.superdimension.com. Accessed January 22, 2004.
30. Grenier PA, Beigelman-Aubry C, Fetita C, Preteux F, Brauner MW, Lenoir S. New frontiers in CT imaging of airway disease. Eur Radiol 2002;12(5):1022–1044.
31. Saam BT, Yablonskiy DA, Kodibagkar VD, Leawoods JC, Gierada DS, Cooper JD, et al. MR imaging of diffusion of (3)He gas in healthy and diseased lungs. Magn Reson Med 2000;44(2):174–179.
32. Schoepf UJ, Costello P. Multidetector-row CT imaging of pulmonary embolism. Semin Roentgenol 2003;38(2):106–114.
33. Gattinoni L, Pesenti A, Baglioni S, Vitale G, Rivolta M, Pelosi P. Inflammatory pulmonary edema and positive end-expiratory pressure: correlation between imaging and physiologic studies. J Thorac Imaging 1988;3(3):59–64.
34. Frerichs I, Hinz J, Herrmann P, Weisser G, Hahn G, Dudykevych T, Quintel M, Hellige G. Detection of local lung air content by electrical impedance tomography compared with electron beam CT. J Appl Physiol 2002;93(2):660–666.
35. IngMar Medical [Internet]. Available at: http://www.ingmarmed.com. Accessed January 22, 2004.
36. Hans Rudolph Inc [Internet]. Available at: http://www.rudolphkc.com. Accessed March 2, 2004.
37. Dräger Medical [Internet]. Available at: http://www.draegermedical.com. Accessed January 22, 2004.

38. Milic-Emili J, Henderson JAM, Dolovich MB, Trop D, Kaneko K. Regional distribution of inspired gas in the lung. J Appl Physiol 1966;21(3):749–759.
39. Comroe JH, Fowler WS. Detection of uneven alveolar ventilation during a single breath of oxygen. Am J Med 1951;10:408–413.
40. Stupar V, Berthezene Y, Canet E, Tournier H, Dupuich D, Cremillieux Y. Helium3 polarization using spin exchange technique: application to simultaneous pulmonary ventilation/perfusion imaging in small animals. Invest Radiol 2003;38(6):334–340.
41. Wagner PD, Saltzman HA, West JB. Measurement of continuous distributions of ventilation-perfusion ratios: theory. J Appl Physiol 1974;36(5):588–599.
42. Ramage JE Jr, Coleman RE, MacIntyre NR. Rest and exercise cardiac output and diffusing capacity assessed by a single slow exhalation of methane, acetylene, and carbon monoxide. Chest 1987;92(1):44–50.
43. MacIntyre NR, Nadel JA. Regional diffusing capacity in normal lungs during a slow exhalation. J Appl Physiol 1982;52(6):1487–1492.

Discussion

Hess: The simulator has become quite important at Harvard and Massachusetts General Hospital, in the anesthesia department. My understanding is that staff get a reduced rate on malpractice insurance if they go through simulator exercises. It's become an important part of showing that clinicians have maintained competence in their practice.

MacIntyre: The anesthesia world has clearly been a leader in this arena. I think much of it is driven by the fact that anesthesia disasters can be extraordinarily expensive from a malpractice perspective. In searching the literature for data supporting these models and simulations, I found that that's clearly where the action is. Whether these things really do decrease the number of anesthesia mistakes is still not well documented. Clearly, though, anesthesiologists who go through this kind of training test considerably better following the training. So it's logical to assume that, much like airline pilots who go through flight-simulator training, this is very likely to substantially reduce mistakes.

Hess: The airline industry has, I believe, shown that simulator training *does* make a difference.

MacIntyre: The airline industry clearly does it. In fact, last night Reed Gardner and Keith Hopper and I got about a quarter of the way from Salt Lake to Calgary and the plane lost the automated trim tabs, which meant they had to fly it manually, and they didn't have the advantage of trimming up the airplane. So they flew us back to Salt Lake without the trim tabs operating. But I must say that as a passenger in the back, I didn't know that there had been anything wrong. Upon landing back in Salt Lake, I asked the pilot if he'd simulated that occurrence before. He said, "hundreds of times." So I was very grateful for simulations.

Chatburn: You mentioned IngMar Medical's lung model, and I just wanted to point out that because it's an active lung model, you don't necessarily have to connect it to a ventilator to do simulations. You can simulate spontaneous breathing, and we're currently using it to study the performance of oxygen masks, for example, because you can simulate the breathing pattern.

MacIntyre: Good point. These active lung simulators are fascinating to me. But even the IngMar Medical system and the Hans Rudolph system, which are pretty sophisticated, still do not quite recreate normal human breathing and other functions. They're useful for teaching and gross evaluations of things like ventilator performance, but they're still not quite where I think they will be in the future.

Gardner: I think the anesthesiologists have clearly documented reductions in their malpractice insurance rates because of their use of patient simulators. A few weeks ago at Hill Air Force Base, where I serve as a volunteer at the veterans hospital, I talked with guys who had been pilots during World War II about their experience with the Link flight trainers and simulators they used back in 1942 and 1943. It's exciting that, 60 years later, medicine is finally catching up.

MacIntyre: Well, I think part of it is that the simulators are getting a lot better. The computer-driven mannequin is really quite remarkable in that you can change so many variables on him. You can literally have his pupils blow, right there while you're looking at him, and watch his blood pressure plummet as he develops a pneumothorax and his saturations go to pot, and you've got to do something about it and do it quickly. Even though it's a simulator, it can be pretty exciting.

Hopper: Have you seen any interesting online simulations?

MacIntyre: I didn't go searching online. I suspect there are some interactive text videos out there with self-assessment components. I don't know about animated models or any of this physiologic or anatomic modeling. Are there good simulation things online, Rob [Chatburn]?

Chatburn: Yes. On Vent World [http://www.ventworld.com] there are some ventilator simulations. They're like virtual ventilators; you can see 3-dimensional views of them and turn the knobs. Amethyst Research has developed a model for the Dräger Evita-4 ventilator, and on that you can even connect a patient to it and get some actual interactions and see waveforms.

MacIntyre: Yes, the Dräger is probably the most advanced. It can create a simulation of its panel coupled to a fairly straightforward passive lung simulator. There is also an active lung simulator; it is fairly simplistic but one of the potential advantages of the system is that it can be used as a teaching tool to show your respiratory therapists and doctors how things work and to help predict the effects of ventilator setting changes. It's not going to predict perfectly, but it's a clever idea and might be applied in the future. So rather than applying a new tidal volume or trying a new inspiratory-expiratory ratio when you're not sure if air trapping might develop or something adverse might happen, the simulation could warn you of possible consequences.

Pierson:* Neil, why do you think health care has lagged so far behind aviation in the development and use and incorporation of simulation into practice?

MacIntyre: We tolerate zero errors in aviation, because accidents are not acceptable. Any crash is unacceptable, and I think all of us in the room who flew here would agree with that approach! In health care, however, we have accepted the idea that biological systems are so complex that a perfect monitoring system cannot be developed. Airplanes are built by engineers and most problems can be anticipated and monitored with redundant systems. That level of system understanding and monitoring capability does not exist in health care. The redundancies and back-up systems on an airplane don't have correlates in health care and thus are not mandated. Moreover, in health care we're trying to cut physician full-time employees to reduce costs. We're trying to get rid of people at the bedside. I think the acceptance of a higher risk in medicine than in aviation is because we are forced to. In the aircraft industry it's a zero tolerance environment, but that's not so in health care.

Pierson: What would you say about the relative complexity and difficulty of modeling and simulation in the respiratory system versus in aviation?

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MacIntyre: As cool as that airplane is that we flew on last night, the human body is probably orders of magnitude more complicated. So I don't think you can simulate the entire human being to account for all possible problems. However, the mannequin simulator is not bad; it can create situations that are close to situations that clinicians should train for. It can model a pneumothorax, an airway obstruction, or a laryngospasm, which are emergencies that all of us should be ready for. So I don't think you have to model the human perfectly, because things that we have now can model a lot of the situations we ought to be ready for.

Hess: All the things you just listed are black-and-white, and a lot of things that we deal with every day in the ICU are various shades of gray. How do you handle that?

MacIntyre: You're absolutely right, Dean. They are shades of gray, and that's why the models are not perfect. But I would submit to you that we're not even handling the black-and-white situations that well. Some clinicians still don't recognize mucus plugging; some are hesitant to react to pneumothoraces and other emergencies, often because they don't recognize them. Air trapping is a classic example. How many times have you had a patient who's developing air trapping and the clinicians at hand are wondering why the blood pressure is dropping and they're looking for dopamine and fluid to hang when all they really need to do is turn down the tidal volume or respiratory rate? I would agree with you that a lot of situations are in shades of gray and are in need of better care, but I think even our black-and-white-situation management is nowhere near as good as it should be.

Nelson: One of the differences between aircraft flight-simulation and patient simulation is that once an aircraft gets old, you can just retire it. Do you think the difference lies in the fact that you can just retire an aircraft, whereas people haven't accepted the fact that everybody is going to die at some point?

MacIntyre: Well, now you're getting to a much more philosophical point. The do-not-resuscitate order is, I guess, the equivalent of retiring the aircraft. Perhaps we ought to be writing do-not-resuscitate orders a little bit earlier than we currently are, but that's a subject for another conference.

Gardner: I have a question about simulators and alarms and alerts. Why do we accept the high false-alarm rate of bedside monitors? We were on that airplane yesterday when the pilot got an alarm, and he dumped some fuel and went back and landed to fix the problem. Why do we accept a high false-alarm rate with our current monitors? It's not simulators, but the simulators could cause our monitors to fail. Why do we tolerate that and why does the Food and Drug Administration tolerate it?

MacIntyre: The issue of monitoring and alarms and where you set your alarm thresholds is complex. The human body is an incredibly complicated system, and there's a lot more "noise" in the monitoring of a human being than there is in monitoring an airplane. On an airplane the monitors are very specific. They're in specific locations, and there are only a certain number of things that can activate an alarm. A human being monitored with the monitors we have today can have many things that activate alarms. A lot of alarms are artifact, so setting alarm thresholds is very tricky. In the ICU, noise pollution from false alarms often leads clinicians to turn alarms off, which is probably one of the biggest hazards in the ICU—turning them off! We need smarter alarms. That's not a role for simulators. The simulators might be able to test alarms, but they would not test them very well, because a simulator is not very noisy. Simulators are very straightforward, more like an aircraft than a patient. Biological systems such as sick patients have a tremendous amount of signal noise—more so than almost any technology we have made.