

Anesthesia Simulators – Technology and Applications

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Abstract

Anesthesia simulators are rapidly becoming more prevalent worldwide. Several types of anesthesia simulators utilizing a variety of technologies are available. High fidelity mannequin-based simulators, low fidelity screen-based simulators, and relatively inexpensive intermediate fidelity simulators have found applications in training, assessment of clinical competence, and research. A number of recent studies support the use of anesthesia simulators and may lead to widespread adoption of simulation in other fields of medicine.

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The fidelity of a simulator describes the degree to which the simulator reproduces the real environment. No simulator is completely realistic, but high fidelity anesthesia simulators utilizing a mannequin, real anesthesia machines, monitors and equipment can recreate the anesthesia work environment quite convincingly. The MedSim (MedSim Ltd., Kfar Saba, Israel) and METI (Medical Education Technologies, Inc., Sarasota, FL, USA) anesthesia simulators include mannequins that are able to breathe, produce breath sounds, heart sounds, pulses, neuromuscular function, and other physical signs [1,2]. Low fidelity anesthesia simulators utilize representations on the computer screen to display and control the patient and monitors. The Anesoft Anesthesia Simulator [3] and GAS MAN [4] are examples of low fidelity anesthesia simulators. Intermediate fidelity simulators, such as the Leiden Anesthesia Simulator [5] and the ACCESS system [6], use a less sophisticated mannequin and facsimiles of real monitors, but at a much lower cost than the high fidelity simulators.

Anesthesia simulators have several applications. They can be used for training, for assessment of clinical competence, for the study of anesthesiologists' behavior, and for the design and evaluation of new anesthesia equipment. In the last few years, anesthesia simulators have grown from a research interest to a widely available training tool. Evidence is accumulating that anesthesia simulators will play an increasing role in training, evaluation and research.

Anesthesia simulator technology

The two commercially available high fidelity mannequin-based simulators (METI and MedSim) have achieved widespread acceptance in the last few years, with over 120 installations in 18 countries. These simulators combine highly sophisticated mannequins with computerized control of the simulation scenario [7]. Anesthesia trainees use real equipment including the anesthesia machine, patient monitors and airway devices to interact with the mannequin as they would a real patient. The mannequins produce a number of life-like outputs. They breathe – producing breath sounds, airway pressures and flows, and exhaled carbon dioxide. The mannequins produce heart sounds, palpable radial and carotid pulses, the electrocardiogram and arterial and central pressures. Arterial pressure can be measured continuously with a direct arterial catheter or intermittently with a non-invasive oscillometric blood pressure cuff. The pulse oximeter signal is reproduced and neuromuscular blockade can be measured at the thumb. The eyes open and close, the pupils dilate, and the extremities move in response to a painful stimulus.

The simulated patient's condition is controlled by a computer program that utilizes mathematical models of physiology and pharmacology to predict the responses to management. Manual overrides allow additional control of the simulation scenario. The initial condition of the simulated patient can be varied to represent many different disease states. Dozens of critical incidents can be created and modified, producing an almost endless variety of patient problems. Hand-held controllers enable the instructor to simultaneously interact with the trainee and control the simulation scenario. Automated drug recognition systems reduce the workload of the simulation controller and allow the instructor to concentrate on the clinical scenario rather than on computer entry.

Actors are often employed in full-scale simulation to play the part of surgeon, circulating nurse, anesthesia technician or other operating room personnel. The actors add an important new dimension to the simulation – namely, interaction and communication among the entire patient care team. Many centers videotape the simulation sessions, which can greatly impact the debriefing process after the

simulation. Videotape capability is also valuable for research applications.

While the trainee interacts with a life-like mannequin, real operating room equipment and actors in a mannequin-based simulator, the entire simulation scenario is displayed and controlled in the graphical user interface of a screen-based simulator. The Anesoft Anesthesia Simulator (Anesoft Corporation, Issaquah, WA, USA) displays the patient and representations of the anesthesia machine and monitors [Figure 1]. The user examines the patient, controls the airway and ventilation, and administers intravenous fluids and medications using mouse-controlled input and a simple menu. Mathematical models predict the simulated patient responses to over 100 medications. The cardiovascular, respiratory and pharmacokinetic-pharmacodynamic parameters can be varied to represent normal patients and those with concurrent illnesses. The models can also be manipulated to simulate complex pathophysiological processes and critical incidents such as malignant hyperthermia [8]. The Anesoft Anesthesia Simulator includes 80 patients covering all aspects of anesthesia – general, regional, cardiac, neurosurgical, pediatric and obstetric – in dozens of emergency scenarios. An automated record-keeping system tracks all the trainee's diagnostic and therapeutic decisions, and allows a trainee to manage a case without the presence of an instructor and to receive feedback at a later time. In addition, a context-sensitive help system provides learning objectives and management advice for each case and displays physiologic and pharmacokinetic plots for the simulations. The help system informs the trainee or practicing anesthesiologist about the important aspects of the case management, making the screen-based simulators an effective independent learning environment to rehearse the management of anesthetic emergencies. Thousands of copies of the Anesoft Anesthesia Simulator are in use in over 50 countries with translations available in English, Spanish and Portuguese.

Several other screen-based simulators are useful for anesthesiology [Table 1]. GAS MAN (MED MAN Simulations, Chestnut Hill, MA, USA) is an excellent simulator for uptake and distribution of inhaled anesthetic agents. GAS MAN utilizes mathematical models and interactive graphic displays to depict the time course of anesthetic tensions in various compartments. Exercises included with the program allow the user to explore alveolar and tissue concentrations, the effect of anesthetic solubility, overpressure, the concentration effect, low flow, and closed circuit anesthesia.

The Virtual Anesthesia Machine (University of Florida, Gainesville, FL, USA) is an interactive simulation that illustrates the flow of gases through an anesthesia machine [9]. This program demonstrates the oxygen fail-safe and several potential failures in the anesthesia machine. The Virtual Anesthesia Machine can be viewed over the Internet.

RELAX (University of Florida, Gainesville, FL, USA) is an interactive simulation program designed to teach

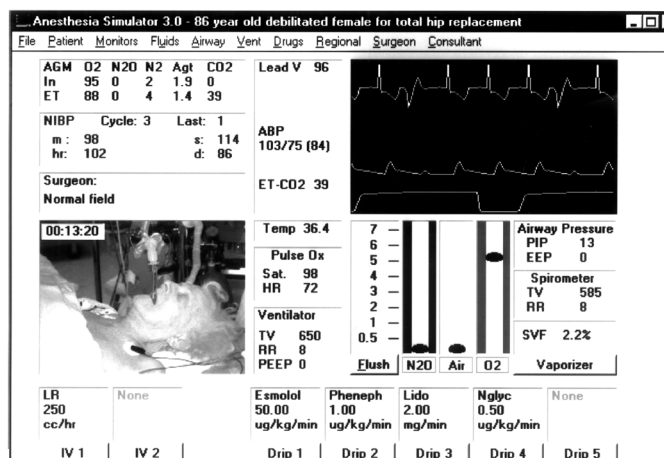


Figure 1. The graphical user interface of the Anesoft Anesthesia Simulator. The user examines the patient, selects the monitors, controls the fluids and ventilation, administers medications, and interacts with the surgeon using a simple menu system.

Table 1. Screen-based anesthesia simulators

Program	Educational objective
ACLS Simulator	Learn and review the AHA ACLS guidelines for management of cardiac arrest
Anesthesia Simulator	Improve response to anesthetic emergencies
Critical Care Simulator	Improve response to emergencies in the intensive care unit or emergency room
GAS MAN	Improve understanding of inhaled anesthetic uptake and distribution
Hemodynamics Simulator	Review cardiovascular physiology, invasive monitoring and vasoactive medications
RELAX	Teach beginning anesthesia residents management of neuromuscular blockade
Sedation Simulator	Improve management of conscious sedation by radiologists, oral surgeons, gastroenterologists, surgeons, and nurses
Virtual Anesthesia Machine	Improve understanding of anesthesia machine gas flow

beginning anesthesia residents about the use of neuromuscular blocking agents [10]. Case-based lessons present the important concepts required for administration and monitoring of neuromuscular blockade. Video animations illustrate train-of-four monitoring, molecular actions at the neuromuscular junction, and pharmacokinetics.

The Anesoft ACLS Simulator (Anesoft Corporation, Issaquah, WA, USA) reviews electrocardiogram rhythm recognition and treatment of pulseless patients according to the American Heart Association Advanced Cardiac Life Support guidelines. In addition to utilizing a graphical user interface, mathematical models, automated record-keeper and online help system, the ACLS Simulator includes an automated debriefing system that highlights all correct and

ACLS = Advanced Cardiac Life Support

incorrect steps taken during the resuscitation. The Anesoft Hemodynamics Simulator reviews cardiovascular physiology, invasive monitoring and vasoactive medications. The Anesoft Critical Care Simulator presents 20 intensive care unit and emergency department scenarios involving acute cardiorespiratory problems. The Anesoft Sedation Simulator is designed to improve management of conscious sedation by radiologists, oral surgeons, gastroenterologists, surgeons and nurses. This program reviews all aspects of conscious sedation including patient assessment, titration of sedative agents, monitoring, and management of common problems associated with conscious sedation.

Anesthesia simulator applications in training

Anesthesia simulators can be applied to many areas of anesthesia training, including physiology, pharmacology, and complex problem solving associated with anesthetic emergencies. Several evaluations of anesthesia simulators have shown their popularity as training devices among anesthesia residents. Mannequin-based simulators were rated highly for resident training by anesthesiologists in Australia (76% favorable) and in the United States (79% favorable) [11]. The screen-based anesthesia simulator program was appraised as an excellent training device (8.5 out of possible score of 10) by 44 resident and attending anesthesiologists at seven different training centers, with no significant difference in evaluation between the institution where the program was developed and other institutions [12]. Other screen-based anesthesia simulators also achieved high approval. The RELAX program received much higher approval ratings for educational benefit and satisfaction than textbook materials covering neuromuscular blockade [9], and GAS MAN was found to be highly acceptable by residents at a university-teaching hospital and at a medical school-affiliated community hospital [13].

At the University of Washington the screen-based anesthesia simulator program is used to introduce anesthesia residents to the management of anesthesia-related emergencies. All second-year anesthesia residents are required to complete 12 cases, exposing them to several major critical incidents including anaphylaxis, malignant hyperthermia, myocardial ischemia, venous air embolism and cardiac arrest. Residents complete these cases individually or in pairs without faculty supervision. The records of the case simulations are reviewed by a faculty member and returned with comments. This is a very efficient system since approximately 10 hours of resident training result from each hour of faculty time invested [14]. We have found that the anesthesia simulator program and critical incident curriculum serve as excellent preparation for critical incident training in the mannequin-based simulator.

Critical incident training in the screen-based anesthesia simulator provides residents with the opportunity to diagnose and treat a number of anesthesia emergencies. Following this training they should have improved cognitive

skills for differential diagnosis of physiological disturbances and treatment algorithms. At this point they are ready for further training with the mannequin-based simulator, concentrating on Anesthesia Crisis Resource Management, which includes team leadership, communication, and workload management [15,16]. We have found that residents who have received screen-based simulation training in diagnosis and treatment of the critical incidents are more effective in their interactions with the rest of the team in the mannequin-based simulator, becoming stronger leaders as their confidence increases.

Experimental evidence demonstrating that anesthesia simulators are effective training devices is starting to accumulate. Several studies support the training impact of screen-based anesthesia simulators. For example, pre-test to post-test scores improved for uptake and distribution of inhaled anesthetics following the use of GAS MAN [13], written test scores for management of neuromuscular blockade improved more for a group of residents that used the RELAX program than the textbook group [10], and retention of ACLS algorithms was better for a group of anesthesiologists that reviewed the ACLS Simulator program than the textbook group [17]. Due to difficulty of study design there is less evidence available for the effectiveness of mannequin-based simulator training. Nonetheless, Chopra et al. [18] were able to measure improved management of malignant hyperthermia in the mannequin-based simulator following mannequin-based simulator training. This study demonstrated that anesthesiologists do learn in a mannequin-based simulator, but it did not compare mannequin-based simulator training to more traditional educational methods such as readings, case conferences or lectures. As stated by Tarver [19], *medicine is likely to have the same problems proving the effectiveness of simulator training as other industries and may have to make the same leap of faith to embrace it.*

Anesthesia simulator applications in assessment

Anesthesia simulators can present reproducible clinical scenarios and therefore have the potential to be used for assessment of clinical competence. Many issues relating to validity, reliability, and practicality of simulator examination must be resolved prior to their use in high stakes applications such as professional certification [20,21]. Construct-related validity evidence establishes whether the performance to be observed represents a legitimate indicator of the capability being assessed. Content-related validity evidence establishes how well the actual content of tasks and observations correspond to the performance to be observed. Criterion-related validity evidence indicates how well performance correlates on relevant criterion measures external to the test. Internal consistency describes the degree to which items that contribute to the score are related and is measured by the reliability coefficient. Interrater reliability describes the consistency of the raters.

The design of a simulator assessment for clinical competence of anesthesiologists must begin with the definition of a competent anesthesiologist. One aspect of competence is the ability to plan and execute a safe anesthetic for a complicated patient, and to manage problems that may arise. The mannequin-based simulator is an ideal environment to evaluate anesthesiologists' management of reproducible intra-operative scenarios utilizing standardized grading systems. Other aspects of competence could also be assessed in the simulator by creating scenarios involving pre-operative evaluation, interactions with the surgeon, postoperative pain management, and communication with the patient and family.

One possible simulator assessment of clinical competence could involve the management of several emergency scenarios, with a score for performance generated using a standardized checklist. Construct validity of this assessment concerns whether the ability to handle those emergencies truly predicts "clinical competence." Scenarios that are too easy will not differentiate weak clinicians from excellent ones, and scenarios that are too obscure may not be relevant to typical clinical practice. The items to be scored in the checklist determine the content validity of the assessment. There must be agreement among experts that the items in the checklist can differentiate correct management of the emergency from poor management. In addition, all simulators have limitations to their fidelity, and clinically unrealistic aspects of the scenario will affect content validity. The reliability of each item in the checklist can be evaluated by examining the performance on that item by the subjects with the highest overall scores. The degree to which the score is affected by the person scoring the assessment is determined by the inter-rater reliability.

Several investigators have begun to study these factors for simulator assessments of clinical competence. Gaba et al. [22] assessed teams of anesthesiologists in their management of malignant hyperthermia and cardiac arrest in a mannequin-based simulator using standardized checklists for technical ratings and ordinal scales for 12 crisis management behaviors. Construct validity seems to be satisfied for this assessment, since competent anesthesiologists should be prepared to manage these two events. Content validity appears to be satisfied for the technical actions, since several experts agreed on the checklists and no deficiencies in the simulations were reported. No comparison of performance in the simulator with other assessments was made so criterion-related validity was not evaluated in this study. Furthermore, no analysis was reported on the internal consistency of the assessment, but there was good inter-rater reliability for technical performance with room for improvement in behavioral inter-rater reliability.

Devitt et al. [23] tested the validity and reliability of another performance evaluation using a mannequin-based simulator. This assessment involved 10 scenarios including circuit leak, bradycardia, atelectasis, coronary ischemia,

hypothermia, missing inspiratory valve, hypotension, pneumothorax, anaphylaxis, and anuria. The rating scale for each problem was no response, compensating intervention, or corrective treatment. Construct validity appears to be satisfied, since these are problems competent anesthesiologists should be able to handle. However, faculty anesthesiologists only scored higher than residents on 6 of the 10 problems, raising doubts about the validity of the assessment of the other 4 problems. No problems with the realism of the simulations were reported to detract from content validity. Criterion-related validity was not evaluated in this study. Reliability of the assessment using Cronbach's alpha statistic showed acceptable internal consistency for the six items that experienced anesthesiologists managed better. Previous studies demonstrated excellent inter-rater reliability of the evaluation method [24]. These studies increase confidence in evaluation of clinical competence using mannequin-based anesthesia simulators, but valid and reliable rating scales need further refinement prior to use in the medical certification process.

Anesthesia simulator applications in research

Anesthesia simulators have been used in several research projects, yielding new insights into anesthesiologists' response to critical incidents and design of new equipment. Using a high fidelity mannequin-based simulator, Gaba and DeAnda [25,26] measured the response of anesthesia residents, faculty and private practice anesthesiologists to five anesthesia critical incidents. They found that experienced anesthesiologists tended to react more rapidly than trainees, but wide variations in response time were seen between incidents and within each group. They also observed that anesthesiologists' method of problem solving appeared to be pattern matching based on the highest frequency explanation for a finding.

Byrne and Jones [27] compared the performance of groups of anesthesiologists with different levels of anesthetic experience in nine emergencies using an intermediate fidelity mannequin-based simulator. The grading scale used in this study was time to solve the problem. They found that anesthetists with less than one year experience had the slowest performances, but found little difference between anesthetists with 1-2.5 years experience and anesthetists with more than 5 years experience, and serious errors were made by even the most experienced anesthetists. This study only tested five subjects in each experience group and therefore conclusions should not be too sweeping. However, this does indicate that after the initial novice period has passed, increasing experience may do little to improve response to anesthetic emergencies.

Schwid and O'Donnell [28], using a screen-based anesthesia simulator, tested anesthesia residents, faculty anesthesiologists, and anesthesiologists in private practice on the management of four anesthetic emergencies. As observed in the other studies, even anesthesiologists with

years of experience made errors. Two inexperienced residents misinterpreted lack of end-tidal carbon dioxide during an esophageal intubation, while all experienced anesthesiologists correctly diagnosed the problem. Success in diagnosis of anaphylaxis improved with experience, but the pattern of errors for management of myocardial ischemia was mixed. While inexperienced anesthesia residents were more likely to give inappropriate drugs and had more trouble recalling and calculating drug infusion rates, experienced anesthesiologists were less likely to treat tachycardia during myocardial ischemia. For ventricular fibrillation an inverse relationship was found between correct management and experience. The time since the last ACLS training was found to be the most important predictor of performance, rather than years of clinical experience. Since anesthesia residents were more likely to have had recent ACLS training, they tended to perform better than experienced anesthesiologists. The observation that more experienced anesthesiologists do not necessarily perform better during all anesthetic emergencies must be taken into consideration when better performance by more experienced anesthesiologists is assumed as a benchmark for validation of assessment tests.

Anesthesia simulators can also be used to assess the design of new anesthesia equipment. Michels et al. [29] produced four critical events on a screen-based anesthesia simulator to assess whether an integrated graphic data display improved detection of the events during anesthesia. Using the simulated events, they were able to measure the response rates of two groups of anesthesiologists to reproducible changes in patient vital signs. Some of the critical events were detected and corrected sooner using the integrated graphic display compared to the traditional monitor with waveforms and digital values.

Conclusion

A variety of anesthesia simulators are in widespread use today. They range in fidelity and cost from expensive computerized and mechanized mannequin-based systems to inexpensive screen-based computer programs. Recent studies support further use and evaluation of anesthesia simulators for training, assessment of clinical competence, and research into anesthesiologists' response to critical incidents and the design of new anesthesia equipment.

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