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Balancing Physiology, Anatomy and Immersion: How Much Biological Fidelity Is Necessary in a Medical Simulation?

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ABSTRACT Physiology and anatomy can be depicted at varying levels of fidelity in a medical simulation or training encounter. Another factor in a medical simulation concerns design features intended to engage the learner through a sense of immersion. Physiology can be simulated by various means including physiology engines, complex state machines, simple state machines, kinetic models, and static readouts. Each approach has advantages in terms of complexity of development and impact on the learner. Such factors are detailed within the article. Various other biological, hardware-based, and virtual models are used in medical training with varying levels of fidelity. For many medical simulation-based educational experiences, low-fidelity approaches are often adequate if not preferable.

INTRODUCTION

There has been a tremendous shift in medical training over the last decade. The venerable approach of passive observation, trial and error, slavish working hours, and lengthy "rounds" is moving toward medical simulation as a mainstay of training for physicians, nurses, and medics. Animal-based laboratories are moving to computer-driven training experiments that replicate the physiology of humans in an environment that encourages experimentation and repetition over one-off opportunities. As computer, material science, and electromechanical technologies advance, there is a concurrent desire to create simulation experiences with ever higher fidelity. Given this, it is important to ask how much fidelity is optimal. This article explores various aspects of biological fidelity with emphasis on physiology and anatomy. The intent is to contrast approaches based on type of training, development effort, and impact on the learner.

PHYSIOLOGICAL FIDELITY

Many training scenarios involve demonstrations of physiological action with an expectation that the learner diagnose a condition based upon the demonstrated physiology, make interventions and view a realistic physiological response as would be seen in a patient encounter. A variety of mechanisms exist that can do this with varying levels of fidelity, dynamism, and effort involved in their creation.

COMPLEX FIDELITY: ANIMAL PHYSIOLOGY

Complex human physiology can be simulated with animal surrogates. Live animals possess analogous physiology that is highly reliable, responds to just about any medication or physical intervention, and allows for realistic interaction with learners. The drawbacks to using live animals include the high cost and effort to maintain the animals, the need to avoid suffering, infectious disease considerations, dissimilar anatomy, lack of repeatability, and the possible or likely loss of the animal.[1]

COMPLEX FIDELITY: PHYSIOLOGY ENGINES

A replicable experience with complex fidelity can be achieved through physiology engines. Physiology engines are computer-coded mathematical models that simulate body systems. Basic physiology engines replicate the cardiovascular system and the effects of hemorrhage, fluids, and medications on the model. Some manikins include such engines.[2] More complex physiology engines are multisystem with large pharmacology libraries and multidrug interactions. An example of a multisystem model is HumMod, created by the University of Mississippi Medical Center.[3] HumMod can readily simulate a wide variety of conditions such as hemorrhage, heart failure, ketoacidosis, or hyperaldosteronism. The results of HumMod outputs are in the form of graphs or data that will closely match results from physiology research studies and textbooks. Finally, biological modeling can simulate biological processes down to the molecular level, though this requires intense computing power and is used for research purposes rather than for education.

Physiology models are a high-end solution that can run in real or accelerated time. They have the capability to mimic realistic physiological activity and can gracefully manage unexpected user inputs. They can cope with the effects of multiple interventions even if those interventions are antagonistic to each other. One problem is that realistic changes in physiology may be too gradual or subtle for the learner to notice unless on-screen indicators readily depict historical trends. Some physiology processes, such as sepsis or chemistry changes, unfold too slowly to be observed during an educational scenario. In these cases, the simulation will appear

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insufficiently responsive and fail to engage the learner. Ironically, gradual responses to user inputs can reduce the user's impression of biological fidelity. The need to closely observe monitor displayswhile tracking ongoing changes distracts the learner from observing the patient.[4] It is often difficult for a simulation to correlate virtual patient verbal behavior or appearance with the state of the physiology engine. Because manikins are constructed mostly out of rigid plastic and few are motorized, they have little capability to change their general appearance. Efforts to show changes in patient appearance in Virtual Reality (VR) simulations based on physiological parameters have been attempted and are maturing (Fig. 1).[5]

Physiology engines are often present in high-end medical simulations. Higher end manikins such as the METI iStan[6] and Laerdal SimMan 3G[7] use physiology models that focus on the respiratory and cardiovascular systems. With these systems, changes in pulse, blood pressure, and respiratory rate are concretely accessible from the physical examination of the manikin as well as on a monitoring display. These engines will respond appropriately to artificial ventilation, chest compressions, and cardiac medications, for example. The high interactivity and close linkage of the physiological response closely replicates an actual critical care encounter. A shortcoming of manikins is the limited behavioral repertoire and the presence of monitoring displays that are often watched over by learners who neglect the physical examination. Manikin features rated by medical students to be most useful include chest rise, palpable pulses, interactive voice, and the vital signs display.[8]

Anesthesia simulation is a common use of physiology engines and it is conducted with manikins, virtual patient avatars,[9] or with a simulated patient monitor (Fig. 2). The most sophisticated manikins can simulate gas exchange on real anesthesia equipment. Because anesthesia training is heavily biased toward pharmacological effects and subtle trends, physiology engines are ideal for this application.[10]

FIGURE 1. Patient with maxillofacial trauma shows the graphical quality of typical high-end VR training systems. Newer models in development can separate out physiological data such as pulse, respiration, temperature, and capillary refill and tie it to relevant animations for pallor, flushing, sweating, anxiety, and distress. Image courtesy of TruSim, a division of Blitz Game Studios.

FIGURE 2. A VR high-fidelity anesthesia trainer uses a physiology engine for precise determination of medication effects. Physiology engines permit combinations of user inputs that may be unexpected by the developer yet still produce reliably lifelike results. HumanSim image courtesy of the Virtual Heroes division of Applied Research Associates.

Physiology engines are also strongly suited to detailed exploratory activities, especially for advanced learners. They are unique in that they permit repetitive explorations while attempting different approaches. This empowers the learner to discover relationships between interventions experimentally. Because of the expense and formidable effort to create physiology engines, the Telemedicine and Advanced Technology Research Center (TATRC), Armed Forces Simulation Institute for Medicine (AFSIM), and the Defense Medical Research Program are sponsoring the creation of an open-source physiology engine as a public resource for all to use freely.[11] It is hoped that the public physiology engine will increase the adoption of this technology and the available corpus of high-fidelity medical simulation content.

COMPLEX FIDELITY: KINETIC MODELS

A different approach to simulated physiology is the SIMapse Nerve Agent Laboratory. SIMapse visually shows cholinergic neurotransmission, the effects of nerve agents, and actions of various nerve agent antidotes on different body systems. The approach of SIMapse is less mathematical and more kinematic; neurotransmitter molecules are graphically depicted in three-dimensional (3D) space and interact with receptors, destructive enzymes, and other agents. The physiological process is graphically showed as actions and behaviors. The results are a very close approximation to known science even though the simulation does not use actual

FIGURE 3. The SIMapse Nerve Agent Laboratory v3 provides a realistic portrayal of nerve agent pharmacology through motion and sound for educational purposes. The program simulates physiological behavior without referring to actual physiological data. It teaches accurate physiology by showing physiology mechanisms, relationships, and pharmacology behavior. Trends over time are depicted as colored sparklines at the bottom of the display.

physiology data, yet it does deliver a high-impact learning experience (Fig. 3).[12]

MODERATE FIDELITY: COMPLEX STATE MACHINES

In practice, physiology engines are neither necessary nor desirable in many educational situations because simpler methods for depicting physiology states are often more practical. Moderate fidelity approaches to depicting physiology are often managed by complex state machines (CSMs) also known as hierarchical finite state machines.[13] CSMs are computer programs consisting of logical rules and decision-tree-based logic that responds to user activity. User actions, simulation timers, and other events trigger different states that change the patient presentation and vital signs.

CSMs are designed for scenario-based training and respond to well-defined, known possible interactions. A major advantage of state machines is that expression of different states is often a marked change that is readily noticed by the learner. It is also easy to indicate changes in patient behavior, vital signs, or appearance because these changes can be concretely tied to a change in the state machine. The CSM approach is ideally suited for training scenarios with limited depth and scope. Simulations appear more responsive to the learner because they provide immediate and visible responses to learner interaction.

The major disadvantage of state machines is that they do not respond well to unexpected, complex, or combinatorial inputs. Undesirable inputs and program complexity are addressed by limiting the variety of possible interventions. Recovery from user errors once a scenario has moved down a decision-tree is difficult to program. Another disadvantage is that each branch point must be individually coded. Adding additional branch points or levels to the state machine can exponentially increase the development work necessary to build the scenario.[14] Medium and high-end manikins often feature this type of state machine and may be packaged with a scenario builder toolkit. In the practice of visiting dozens of simulation centers in the United States, it is the author's observation that few centers go through the effort to create custom scenarios with a toolkit. Instead, they tend to rely on scenarios provided by the manufacturer. VR scenario and game-based training often use the CSM model.

Another medium-fidelity approach is to couple a state machine to some sort of physiology model. When the U.S. Army Field Management of Chemical and Biological Casualties Course required a nerve agent pharmacology trainer targeting less advanced learners than would be appropriate for the SIMapse Nerve Agent Laboratory, the SIMapse engine was adapted for a multimedia application called Nerve Academy.[15] Nerve Academy uses an on-screen lecturer who delivers mini-lessons coupled with preprogrammed use of the SIMapse engine. It also includes numerous interactive activities at the end of mini-lessons that trigger events in the engine. The result is a responsive learning experience with high fidelity that is very easy for the learner to use.

The advantage of combining a limited set of inputs or a state machine to a physiology model is that it is possible to have high biological fidelity and visible trends in data although allowing for simplicity of use and well-defined, responsive changes in the appearance of the model. Another advantage to coupling a limited interaction set to a physiology model is that doing so greatly simplifies the complexity and sophistication required of the model by limiting the parameters the model has to account for.

LOW FIDELITY: SIMPLE STATE MACHINES

Most educational scenarios and simulations in medicine use low physiological fidelity to good effect. Low-fidelity approaches require less technology, effort, and sophistication to pull off and, therefore, are easier to author.

Patient simulations can use simple state machines (SSMs) to great effect. SSMs consist of 3 or more fixed states that alter the appearance, communication, and physiology data of the simulated patient. They lack branching and conditional

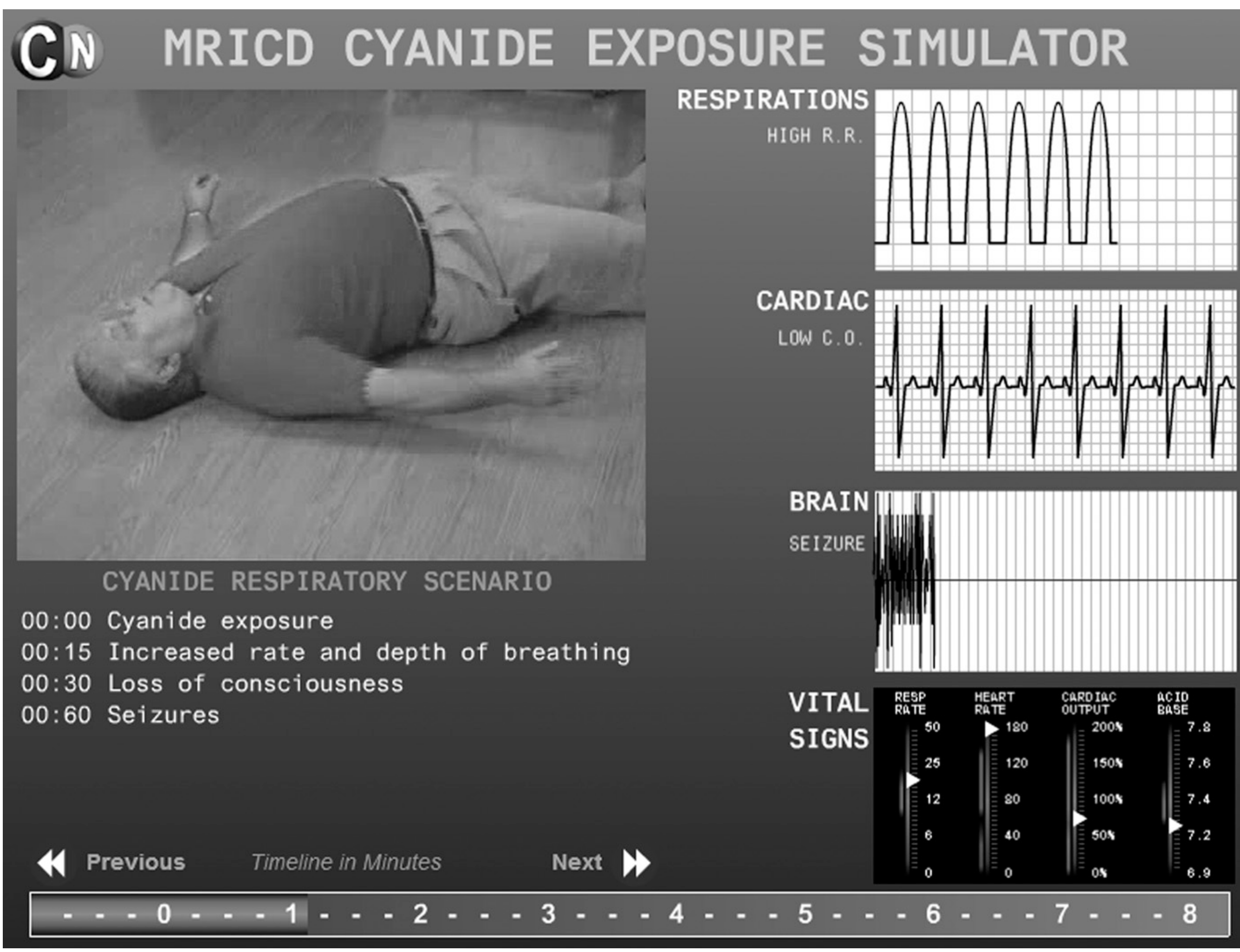

FIGURE 4. The Cyanide Exposure Simulator is an SSM consisting of 7 frames. It uses simple animation effects to create the impression of live physiology. Numerous physiology displays are hand-drawn graphics that are progressively revealed, offering the illusion of real-time monitoring. Except for button controls, the simulation required absolutely no programming. This example shows that low-fidelity approaches can convincingly convey a dynamic process to learners.

features of the more complex CSMs yet still offer many of their benefits. They are especially useful in adding a dynamic appearance to a simple case presentation when creation of an in-depth simulation is too resource intensive. They can be created with simple technology, such as web pages, interactive animations or PowerPoint (Microsoft Corporation, Redmond, Washington).

An example familiar to the author is a simple animation-based application called the "Cyanide Exposure Simulator."[15] The simulation is usually deployed during large classroom sessions. It consists of 7 possible states that show an inhalational exposure to cyanide and the effects on human physiology. States are selected with two buttons to traverse back and forth through a timeline. Each step down the timeline plays a 10- to 15-second video clip, changes signs, and alters graphs (Fig. 4). The overall effect is that of a dynamic simulation that seems to portray a wealth of biological data. The video with the actor conveys the clinical picture. The rolling displays for the pneumograph, Electrocardiography, and Electroencephalography are fixed lines that are progressively uncovered, producing the illusion of live monitoring. Vital signs of respiratory rate, heart rate, cardiac output, and blood pH are represented by triangle indicators on linear gauges. The transition between states is a simple animation that moves the indicators over 3 seconds. The impression of this gradual transition is that of physiology that is changing with the timeline. In truth, the vital signs presented are generic as everything else. The cyanide simulator effectively portrays cyanide effects even though no detailed physiology data are ever conveyed to the learners. In fact, providing such level of fidelity that includes more detail would diminish educational effectiveness.[16] Based on user feedback as a developer, the author finds that most learners are unlikely to detect a difference between this simple state model and an expensive version that uses a physiology engine if the physiology changes seem logical.

SSMs can also be used for intervention-based training. Virtual Nerve Agent Casualty (VNAC) pushes the envelope for a simple state model to simulate treatment of a severe nerve agent exposure.[17] Video of a patient is played although the learner interacts by dropping antidotes and interventions onto the patient display. The state model plays a new video with each intervention and counts up correct interventions until a required quantity is reached. At this point, the state is changed that alters data on the screen (Table I). The simulation requires persistence on part of the learner but results in a satisfactory simulated experience despite the fact that the biological fidelity is low. A drawback of this simple application is that it is very unforgiving of learner errors and does not allow for a corrective pathway if treatment errors are made.

LOW FIDELITY: GAME-BASED APPROACHES

A game-based approach to depicting physiology is the health score. Health scores are simple numeric or bar graph representations of health. They consist of a point-based score or 100-point scale and are often called hit points. This very simple and low-fidelity representation of health status is ubiquitous and is readily understood by game players. In games, the player's avatar loses hit points upon receiving damage. Losing all hit points results in death of the player. Hit points tend to gradually regenerate or are restored by activating plus-ups.

Medical simulations can also exploit health scores. One approach to health scores uses trend zones. For example, one can split the range of hit points with low, stable, and high zones (Fig. 5). High health scores will improve until health is full. Scores in the stable zone will improve very slowly and scores in the low health zone will automatically decrease. Simply setting the health score based on a virtual patient's disease or improvement after intervention will now be followed by an automatic, ongoing action. This action can be

TABLE I. Simple State Model of Virtual Nerve Agent Casualty (VNAC). (States 4 and 5 are Not Depicted for Clarity.) VNAC is a Product of the U.S. Army Medical Research Institute of Chemical Defense Chemical Casualty Care Division

			State 6	State 7
Initial State	State 2	State 3	Final State for Success	Final State for Failure
Conditions Default	Activating Conditions 3 Atropine 3 Oxime 1 Diazepam	Activating Conditions 4 Atropine 3 Oxime 3 Diazepam	Activating Conditions 15 Atropine 4 Oxime 4 Diazepam	Activating Conditions 5-Minute Delay in Treatment, Seizures Not Controlled in 10 Minutes, An Error is Made
Vitals: Heart Rate 140 Respiration: 30 Blood Pressure: 40 Systolic Secretion 4+ Bronchospasm 4+ Twitch+ Seizure + "The patient is twitching and having difficulty breathing. . ."	Vitals: Heart Rate 120 Respiration: 24 Blood Pressure: 60 systolic Secretion 3+ Bronchospasm 3+ Twitch + Seizure +	Vitals: Heart Rate 130 Respiration: 20 Blood Pressure: 100 systolic Secretion 2+ Bronchospasm 2+ Twitch – Seizure –	Vitals: Heart Rate 160 Respiration: 13 Blood Pressure: 140 systolic Secretion– Bronchospasm– Twitch– Seizure– "Great job, the patient is stable for transport"	Vitals: Dead "You just didn't treat her well enough"

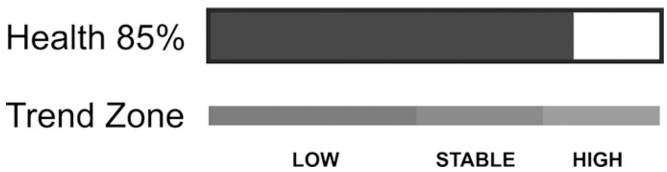

FIGURE 5. Health Scores represent total health by points or a percentage displayed on a bar graph. This type of display is not capable of showing historical values, but the score can be observed to change if the learner watches it. The above sample includes a legend that depicts trend zones that would otherwise be invisible to the learner. Health scores in the low-trend zone automatically decline and scores in the high zone automatically increase over time. The score does not change within the stable zone. A little additional math creates a surprisingly vibrant and useful indicator of patient health for game-based learning.

enhanced further by adding nonlinear response curves.[18] With trend zones, the score will always be moving, encouraging the learner to intervene. This approach requires very little development effort.

A more sophisticated approach from the gaming world uses score modifiers. Score modifiers come in four basic forms: instant damage, instant healing, damage over time (DoT), and healing over time (HoT). Instant modifiers are a one-time reduction or improvement to the health score. DoT is a continuous score reduction over a specified amount of time. In the example of a bleeding virtual patient, the health score will progressively decline on the screen as bleeding is a DoT effect. If the learner gives the patient a blood transfusion, perhaps some points will be added to the health score, but the score will continue to decline. If the learner intervenes and stops the bleeding (i.e., tourniquet), then the DoT effect is cancelled out. Applying a blood transfusion (instant healing) will now permanently increase the score because the DoT effect is no longer present. Careful application of different score modifiers can mimic responsive and sophisticated physiology. The drawback is that health is being represented by a single moving bar; such a display typically does not show historical trends. Learners who grew up with video games are accustomed to this health scores even though it is not widely used for medical simulations. Further research is needed to assess the impact of health scores on learner perception.

TATRC is currently working with BreakAway to develop a multiplayer online hospital-based mass casualty simulation for coordinating a response to a very large number of casualties (Communication with Jennifer McNamara, CBRNE-GAME Leader). The clinical role in the game involves triage and treatment for hundreds of casualties. The patients will use a blended model, including a health score, score modifiers, and a simple state model with only three descriptions of patient presentation. Use of these shortcuts allows for patients that change noticeably over the course of the exercise and act responsively to player intervention. The learner will be busy prioritizing and selecting treatments and will likely not take notice that the fidelity is shallow. In fact, the simulation depends on the fact that fidelity is shallow so learners focus on "the big picture." The question of how the learner perceives fidelity in the simulation will be the subject of game test research.

LOW FIDELITY: STATIC PRESENTATIONS

The most common method of depicting physiology is through a static presentation. Static presentations state vital signs and provide a case in written or verbal form. Static presentations can have as little or as much detail as desired with little effort required on the part of the author. This format is commonly used in written tests, magazines, multimedia, and web pages to effect and is well known to medical learners. While the advantages involve ease of authorship and distribution, the disadvantage is the lack of interaction. This format does a poor job of showing progression and the effects of intervention. Static presentations have strictly right and wrong answers without consideration of creative possibilities. This format is the most common type of educational patient case.

PHYSIOLOGICAL FIDELITY: APPLICATIONS

Each approach to depicting physiology has its own best use (Table II). Advanced learner simulations and exploratory activities are well suited to physiology engines. Interactive case scenarios can be conducted with a physiology engine, but CSMs and SSMs are usually preferred because of the relative simplicity of development and lower computing resource requirements. Because state machines consist of a few dozen calculations to perform versus thousands for a physiology engine, state machines require fewer computing resources to run. Although computers are always becoming more powerful, the resource requirements to run a physiology engine in real time become significant when attempting to run 100 or 1,000 simultaneous instances within a serious game. Another area where the logical simplicity of state machines is preferable includes low power and low computing resource environments such as mobile devices and tablets. Game-based training is well suited to CSMs and health scores. Presentations and mini-activities with few options are well suited to SSMs. Case studies are most easily written as a static presentation, though adding a state machine can increase the interactive possibilities. The available number of quality medical training scenarios is limited by the effort required to develop them. Fortunately, the majority of medical scenarios do not require high physiological fidelity. Clever developers use a number of tricks to create the impression of physiological fidelity. These techniques include visible responsiveness to user input and use of animation.

ANATOMICAL FIDELITY

Medical simulations use anatomy in both virtual and physical environments. Anatomic features are most important for training invasive procedures though they are also useful in practicing diagnostic skills. Various anatomical approaches are identified here along with their strengths and weaknesses.

Live models such as human standardized patients have extremely good fidelity and are useful for physical diagnosis

TABLE II. Comparison of Approaches to Virtual Patient Physiology

	Physiology Engines	Complex State Models	Simple State Models	Health Scores	Static Presentations
Handling of Unexpected and Complex Inputs	Easy	Difficult	Impossible	Moderate	N/A
Ease to Correlate Visualization With Model	Difficult	Easy	Very Easy	Moderate	Very Easy
Response to User Input	Gradual	Instant	Instant	Gradual/Instant	None
Graceful Recovery From Learner Errors	Yes	Challenging	No	Yes	N/A
Suitability for Lengthy Scenarios	High	Low	Low	High	Low
Biological Fidelity	High	Moderate	Low	Low	Low
Typical Perception of Biological Fidelity	Moderate–High	High	Low	Moderate	None
Best Use Scenario	Advanced Simulations and Exploratory Learning	Interactive Case Scenarios and Game Based Training	Interactive Case Scenarios, Presentations and Mini-Activities	Game-Based Training	Case Studies
Development Effort	Difficult	Moderate	Easy	Easy	Very Easy

skills. Major limitations include the limited availability of pathologies that are stable enough to use this technique. The expense of hiring standardized patients is enormous and humans are not suitable for rehearsing invasive procedures.[19] Cadavers offer many advantages for anatomical realism and some can even be partially reanimated if fresh, but they are expensive, limited in their availability and administratively burdensome to possess.[20]

Live animals have their own limitations. They can be used for training purposes for both examination and invasive procedure training, though there are important ethical restrictions and precautions involved in their use. Their superior tissue properties are not yet achievable by artificial means. They can be operated on and do all the physical things that humans do. They do not require a team of developers to bestow their capabilities. Differences between the animal model and true human anatomy are a disadvantage to this approach.[21]

Task trainers are simulators that consist of discrete body parts or regions for training a specific task. Task trainers have been developed for intravenous access, central line placements, intraosseous access, lumbar puncture, colonoscopy, tracheal intubation, and many other procedures. They allow for repetitive practice of physical procedures at low cost. They are usually constructed of molded plastic and rubber-like compounds. They tend to have suitable anatomic landmarks but can be lacking in suitable tissue properties.[22] Ideal tissues will feel like flesh and bone and include appropriate compliance, texture, moisture, bleed and traction properties. Most task trainers fall far short of this ideal. Crude materials also limit fidelity for training for physical diagnostic skills such as palpation of blood vessels and organs.[23] Task trainers also require maintenance and replacement of consumable parts. Despite limitations, even unsophisticated task trainers have been proven effective in medical training.[24]

Manikins known to the author fall short on anatomical fidelity because they lack internal anatomy such as tissues, muscles, bones, organs, and vessels. They are accurate at a gross level and may include palpable pulses, chest rise, palpable ribs, and other features. Current manikins do not articulate naturally, lack muscle tone, and cannot be operated on. The skin is rubber-like or plastic and they lack realistic tissue properties. Nevertheless, they are useful in many training situations and numerous procedures can be rehearsed on them. Current manikins do tend to have sophisticated airways. They are often best for scenario-based training and demonstration of decision making and proficiency for a sequence of events than specific skill rehearsal that is often better performed with a dedicated task trainer. Depending on the use, even very basic models may be suited to medical training if the scenarios are designed properly.

A less well-known, but growing approach is the high-fidelity physical model. Physical models are task trainers for surgical intervention. They combine soft plastics, gelatinous tissue substitutes, composites, and cloth to represent the internal anatomy of an organ or wound and are often moulaged to represent a specific pathology. These often disposable trainers include simulated skin, bone, nerves, muscles, and tissue planes.[25] Some are capable of blood flow and hemorrhage. Common physical models include limbs, the inguinal canal, and other areas of the body. They allow for surgical rehearsal at low cost and are a very practical technology.

VR systems use a 3D human representation on a computer display. For surgical purposes, they are viewed stereoscopically on a 3D screen or with display goggles. They usually include realistic appearing surgical manipulators or a 3Dpen-like device with haptic feedback. Enormous advances in graphical computing power now allow for realistic 3D portrayals of both external and internal human anatomy with detailed surface textures and appearance. These recent graphical advances are so dramatic that VR simulations from even a few years ago now appear antiquated. Graphical realism is no longer limited by the computer. It is limited the effort and expense of creating the 3D models and artwork. The technology behind the haptics (sensation of feeling), although awkward to get used to, can provide uncanny sensations of moving tissue, a scalpel, or hard points underneath the skin.[26]

VR surgical systems are extremely difficult to develop material for and remain very expensive. Because of this, the available library of procedures and scenarios using this technology remains small. Worse yet, content developed on one system is not transferable to that of another manufacturer. The AFSIM and the National Capitol Area Simulation Center are attempting to ameliorate this through Tri-Service Open Platform for simulation (TOPS) by specifying a common interface between software and hardware systems (Communication with TOPS Prinicipal Investigator, Alan Liu). AFSIM is also working to develop an open-source haptic-enabled surgery toolkit to promote additional content development and advancement of this technology.

INTERACTIVITY AND NARRATIVE

Fancy graphics, accurate anatomy, and physiological fidelity are not the only, nor the most important features of a successful medical simulation. The quality of a simulation-based training experience depends on successful engagement with the learner. Achieving engagement depends on a sense of immersion, successfully executing visuals, responsiveness, and a good narrative. Creating the sense of immersion is more important than 3D or the level of visual detail in the simulation. It depends on having a consistent simulation world with things to do or see that are interesting to the learner.[27] Simulations can achieve engagement with the learner more successfully if actions they perform in the scenario are followed by a visible or audible response.[28] Responsiveness connects the learner to the scenario. In the case where virtual humans are encountered, responsiveness establishes likeability and rapport with the learner. Nonverbal cues and gestures, even random ones, increase this sensation of rapport with the scenario and virtual patient. For these reasons, factors such as "response to user input," "perception of biological fidelity," and other factors are listed in Table II, which is a comparison of approaches to virtual patient physiology. This table is based on the author's experience as a developer and interactions with hundreds of learners using various medical simulations. In addition to design choices such as the level of fidelity required and the amount of development effort one wishes to expend, one should not neglect the impact of old-fashioned storytelling; research strongly shows that narrative is a successful tool to engage people.[29]

CONCLUSION

When it comes to methods to depict physiology in a medical simulation, some generalizations can be made (Fig. 2). Physiology engines excel at advanced simulations and exploratory learning where sophisticated learners want to try unexpected things and see accurate responses. Examples of this include anesthesia trainers and toxicology simulations. Complex state models are useful for interactive case scenarios and game-based training because they provide predictable behavior, excellent responsiveness, and can be reasonably complex while appearing to have high fidelity. Simple state models are well suited to interactive case scenarios, lecture presentations, and mini-activities because they are very easy to author yet are interactive and responsive to user input. Health scores are ubiquitously used in entertainment titles but not so much in medical simulations. They have the advantage of easy implementation, being dynamic and that they are a familiar format. Further research is needed to determine their suitability and acceptance of health scores in medical simulations. In fact, the author recommends that those intending to create medical simulations use the simplest technology possible that achieves the learning objectives. Either way, further research is needed to obtain data regarding learner perceptions of simulations that use these technological approaches for physiology as the extant literature is sparse compared to research on graphical realism, immersion, and narrative.

Biological fidelity in medical simulation is not an end in and of itself. Physiology, anatomy, interaction, narrative, and the technology behind them represent an array of tools. The choice of these tools must be determined by educational objectives. The fact that more complex systems require more time, effort, and money to create means that unnecessary use of high fidelity results in less available training content overall. Although some applications rightly require exacting fidelity, many do not. Medical educators should choose the most appropriate level of technology that achieves the goal. When doing so, they may often find that the level of fidelity required is lower than what they initially expected.

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