PART ONE
Fundamentals of Medical and Health Sciences Modeling and Simulation

1 Introduction to Modeling and Simulation in the Medical and Health Sciences

CATHERINE M. BANKS

INTRODUCTION

Technological advancements have paved the way for new approaches to modeling, simulation, and visualization. Modeling now encompasses high degrees of complexity and holistic methods of data representation. Various levels of simulation capability allow for improved outputs and analysis of discrete and continuous events, and state-of-the-art visualization allows for graphics that can represent details within a single shaft of hair [1]. These technological developments were first exploited among the engineering and computer science disciplines; however, the expanding body of knowledge and user-friendly applications of modeling and simulation (M&S) have resulted in applications across the disciplines. As such, M&S is at the forefront of multidisciplinary collaboration that integrates quantitative and qualitative research methods and diverse modeling paradigms. Significantly, these modeling tools are capable of representing many aspects of life, including life itself. Case in point: the use of M&S in the medical and health sciences (MHSs).

Practitioners in the MHSs are engaging M&S to explore and understand some fundamental aspects of health care, such as human behavior, human systems, medical treatment, and disease proliferation. The training tools available to people in these fields include the three primary modes of M&S: live, virtual, and constructive. These modes facilitate the development of mathematical, physical, computer, and human models. Thus, it can be said that *medical and health sciences is an evolutionary, interdisciplinary process of model development and simulation design requiring the expertise of developers* (*M&S*

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experts) *and users* (*medical and health care trainers and practitioners*) *to facilitate a seamless mode of information transmission.* The information discussed in this book is designed to educate future members of the MHS M&S community toward developing and perfecting a seamless mode of information transmission in the health care domain via M&S.

Consider this seamless mode of information transmission as having two interrelated meanings. The first is a focus on basic M&S as it pertains to the MHSs, in which the objective is to create environments whereby precise information *transfers directly to* or is *discovered by* the health care provider. The second meaning, and one that serves as the impetus for this book, is that M&S *developers* and *users* must share expertise, requirements, and criticisms while recognizing limitations and expectations regarding model development and simulation design. Any expert modeler will freely admit that modeling is not easy: The more complex the system or entity to be represented or characterized, the more difficult the task of modeling it. Added to that is the difficulty of modeling the organic, dynamic nature of the human body. Similarly, medical trainers and practitioners recognize the dynamism of the body; therefore, they cannot always provide discrete, static portraits of the anatomy or quantitatively convey degrees of pain. Therefore, both developers and users must appreciate the parameters and the tasks that each one encounters to best facilitate a seamless mode of information transmission. In this chapter we introduce the current challenges of developing and engaging M&S in the MHSs. We present the role of M&S as two complementary activities in health care studies: the development of tools and the training and use of those tools. An introductory overview of these concepts is a good place to start.

MODELING AND SIMULATION IN THE MEDICAL AND HEALTH SCIENCES

The M&S body of knowledge is expanding as interest in the discipline and application of models and simulations increases. The academic programs in which the core curriculum of M&S is taught are found in the engineering and computer science departments. These disciplines dominate the body of literature, which is grounded in mathematics, engineering, and computer science. As M&S applications and user friendliness increases, so will student (and user) interest. For many students M&S serves as a way to explore hypotheses and serves as a training tool. This has also been the case with students studying medicine and health sciences; the long history of medical modeling is proof of that.

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There is, however, a growing concern that a lack of understanding exists on the part of the MHS student when using M&S solely as a training tool. This deficiency creates a void in understanding the theoretical underpinnings of the M&S. Conversely, engineering students as M&S developers must appreciate the fact that acceptance of medical applications of M&S depends on such issues as performance, robustness, and accuracy—attributes that require medical expertise and/or input at the development stage. A cursory review of the MHS M&S literature sheds light on the fact that a gap exists in the scholarship that disconnects developer and user.

As a whole, the MHS M&S body of knowledge is comprised of books, journals, and conference proceedings that span both the development and application sides of the domain. Probably the most complete MHS M&S subarea in the literature is the technical–developer community responsible for *visualization and imaging*. Academic training for visualization and imaging is generally found in the electrical and computer engineering and/or computer science disciplines, both of which have been perfecting the development of visualization and imaging technology. In fact, there is a long tradition of scientists and engineers who illustrate their work with graphics that include anatomical illustrations and computer images to provide representations to store three-dimensional geometry and efficient algorithms that render these representations. Other developer-side contributions to the body of literature include subareas such as *biomedical* and *devices and systems: technology and informatics*, which speak to computational intelligence and medical simulation as well as to developing next-generation tools for medical education and patient care.

Biomedical engineering is the application of engineering concepts and techniques to problems in medicine and health care. This is a relatively new domain with typical applications in prosthetics, medical instruments, diagnostic software, and imaging equipment. Computational intelligence techniques consist of computing algorithms and learning machines, including neural networks, fuzzy logic, and genetic algorithms. One such study designed for graduate-level students is the 2008 Begg et al. text discussing state-of-the-art applications of computational intelligence in cardiology, electromyography, electrocephalography, movement science, and biomechanics [2]. Numerous biomedical handbooks are available. A notable text is *Medical Devices and Systems* edited by Bronzino [3], which introduces the term **clinical engineer**. These engineers are closely aligned with **biomedical engineers**, whose primary focus areas include the development of biocompatible prostheses; various diagnostic and therapeutic medical devices such as clinical equipment to microimplants; common imaging equipment such as MRIs and EEGs; biotechnologies such as regenerative tissue growth; and pharmaceutical drugs and biopharmaceuticals. Clinical engineers also apply electrical, mechanical, chemical, optical, and engineering principles to understand, modify, or control biologic systems; and they assist in diagnosis and treatment.

Also found on the user–educator side of the body of knowledge is a significant series entitled *Medicine Meets Virtual Reality* [4–6]. These edited volumes of short papers present different *approaches to* and *uses of* simulation. As a whole the series is committed to knowledge sharing and building bridges via breakthrough applications in simulation, visualization, robotics, and informatics as well as experiences between physicians in all specialties, scientists in various disciplines, educators, and even commercial entities that serve as retailers of this technology. This *bridge building* is significant and necessary. Additionally, the series includes cognitive and behavioral assessments derived from simulation trials used for examining a variety of scenarios, ranging from enhancing dental treatment processes to examining schizophrenia.

Among the numerous essays in the Westwood et al. volumes is one of special interest to M&S educators, as it explains the need to develop body of knowledge repositories and commonly agreed upon definitions for the medical M&S vocabulary. In "Visualizing the Medical Modeling and Simulation Database: Trends in the Research Literature," the authors, Combs and Walia, present a structured categorization of the literature (choosing to bin it into eight categories) as well as general terminology that can serve as a baseline for a common lexicon, such as *procedural simulation* and *telemedicine* [4].

All students of MHS M&S need to stay current with this expanding body of literature to understand the basic theoretical underpinnings of M&S technology and the new tools available to practitioners. These tools include **engineered devices** such as the cochlear implant, the defibrillator, and the pacemaker, as well as novel applications stemming from the field of **biomechatronics**, which merges humans with machines. **Robotics** is also providing innovative approaches to the human–machine interface as well as in clinical procedures. Computer-based M&S has led the development of **training simulations** where medical practitioners can hone their skills and expand their experience through the use of haptic devices, digital models, and imaging capability.

The body of literature draws attention to the divide or gap that exists between the technical engineer who develops M&S tools and the practitioner who applies the methods. Therein lies the challenge: to balance of both worlds. Students who master the challenge will have accomplished a necessary, meaningful, and useful contribution to these disciplines. A good place to start that mastery is a basic understanding of the terminology and concepts relevant to the study of M&S in the MHSs.

Definition of Basic Terms and Concepts

Throughout this book the reader will be introduced to a number of terms and concepts in the MHS domain. Appropriate for this chapter is a brief introduction to some of these terms and concepts, beginning with the fundamental modes of M&S and the general nature of the model itself. (See Chapter 2 for a detailed review of this information.)

The discipline of M&S and the use of M&S applications is grounded primarily on analysis, experimentation, and training. **Analysis** refers to the investigation of a model's behavior. **Experimentation** occurs when the behavior of the model changes under conditions that exceed the design boundaries of the model. **Training** is the development of knowledge, skills, and abilities obtained as one operates the system represented by the model. There are three **modes of M&S**—live, virtual, and constructive—and they are the same no matter what discipline makes use of M&S. Any discussion of these modes should originate from the discipline of the M&S perspective. This facilitates the establishment of a common terminology. It also relates this terminology to concepts found in the MHS domains to help bridge the gap between developers and MHS practitioners. First, there is the **live mode** approach, the concept of using real (live) people employing real equipment for training purposes. Next, the **virtual mode**, which is perhaps the most fascinating, as virtual operating rooms and synthetic training environments are being produced for practitioners and educators at breakneck speed. In this mode, real people are employing simulated equipment to improve physical skills and decision-making ability. Finally, there is the **constructive mode**, used as a means of *engaging* MHS M&S. In constructive simulation, simulated people and simulated equipment are developed to augment real-world conditions for training or experimentation purposes.

All modeling originates from a theoretical perspective, and it evolves from a conceptual model. The nature of the model can be computational or physical. **Computational models** exist in a purely mathematical form such as a series of equations, or in an algorithmic form implemented in a digital computer. **Physical models** can be manikins that contain representations of human anatomy used for the purpose of practicing surgical or diagnostic procedures. Computational and physical models directly support the three modes of M&S. However, computational models are most closely associated with the constructive mode, whereas physical models are commonly engaged in a virtual mode. (These modeling natures are discussed in detail in Chapters 3 and 4.)

It is important that developers of MHS M&S understand the modes and the nature (or origin) of a model. This information is necessary in determining what type of model would best serve for MHS training or as a practitioner's

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tool. Training and tools are the two primary categories in which many MHS applications of M&S can be found.

Modeling and Simulation Applications

Generally speaking, the application of models and simulations are found in two broad areas. The first area is research, which encompasses such things as humans as models, human systems modeling, and disease modeling. **Humans as models** makes use of real people so that they can portray or mimic particular disease symptoms to provide an interactive diagnosis training experience for MHS students and professionals. Naturally, this type of modeling is included in the live mode. (This type of modeling is discussed in detail in Chapter 5). Conversely, **human systems modeling** introduces analytical and computational methods to model and simulate medical principles as a way of understanding how the organ systems control functions of the body. This type of modeling is interdisciplinary, as it makes use of expertise from numerous disciplines, such as biology, mathematics, and computer science. (This topic is reviewed in detail in Chapter 6.)

The second area is usage and education, such as in training and patient care. The use of mechanical means to facilitate less invasive surgical procedures—robotics—is discussed in Chapter 7. Much of the M&S education in an MHS relies on current tools that are used primarily as training applications: for example, a fully immersive **virtual operating room** fitted with a simulated patient and both real and simulated equipment. The operating room is designed to provide training in judgment and decision making for members of surgical teams using both real and virtual team members. M&S technology is also engaged to augment training with **standardized patients** (i.e., people who realistically portray patients—used to teach and assess communication and other clinical skills). **Modified stethoscopes** allow the learner to hear abnormal heart and lung sounds when placed on a normal, healthy, standardized patient. (The topic of training is addressed in Chapter 8).

Patient care deals with using simulation to improve or contribute directly to a patient's overall health and well-being. Simulation makes it possible to test new protocols and to design new products to achieve an improved level of health. (See Chapter 9 for a discussion of patient care.)

RESEARCH AND DEVELOPMENT OF MEDICAL AND HEALTH SCIENCES M&S

As M&S educators, the editors of this book found it interesting that the MHS M&S community, a subset of the M&S community at large, would refer to the ***science of simulation*** as a separate entity or discipline. This encouraged the editors to conduct an analysis of M&S in the MHSs in an attempt to bring together under one umbrella a shared lexicon. Frankly, until researching the resources for this textbook study, neither editor had heard the term *science of simulation* (and Dr. Sokolowski has a Ph.D. in modeling and simulation!). As such, a book by Kyle and Murray, *Clinical Simulation: Operations, Engineering, and Management*, drew attention [7]. That text addresses simulation as a core element of training in medicine, surgery, clinical care, biomedical engineering, and the medical sciences. Specific to this study was an enlightening essay by Richard M. Satava of the University of Washington.

Satava speaks of the collective support for using simulation as a medical educational tool on the part of the Residency Review Committee of the Accreditation Council on Graduate Medical Education. The council now requires that residency programs have simulation as an integral part of their training programs. The American College of Surgeons has also recognized this transformation and is certifying training centers to ensure the quality of simulation training provided. For medical professionals serving as educators, simulation has become what Satava calls *a training environment with permission to fail*, where students are *taught by errors*. Thus, as part of a broader M&S education program, this book is designed to encourage the M&S developer community to take hold of the *science of simulation* subset and integrate it into the M&S body of research and development. To separate the two is confusing and nonproductive, and it perpetuates a disconnect between developer and user. Only recently have the challenges posed by this dichotomy been realized.

In the 2005 report by the National Academy of Engineering, the call for engineering and health care partnerships rang out loudly. By February 2009, medical simulation legislation had been enacted. Appropriately called *SIMULATION* (Safety In Medicine Utilizing Leading Advanced Simulation Technologies to Improve Outcomes Now), this legislation extends the benefits of advanced medical simulation technology to the civilian health care system and calls for the establishment of simulation technology in medical, nursing, allied health, podiatric, osteopathic, and dental education and training protocols.

M&S has been grappling with accurately characterizing or representing human behavior in models developed from real-world case studies. This is a challenge because human behavior is difficult to evaluate (as it is unpredictable and dynamic) and to quantify. The human body is equally unpredictable and dynamic; thus, it is difficult to model from a developer side. The inherent uncertainty within the model and/or the simulation tools calls to question user confidence. Yet, one must ask: What is the alternative? Simply refuse to model, or attempt to model, human systems or case studies that reflect degrees of uncertainty? No. M&S educators are compelled to press forward with enhancing modeling capability in an effort that best represents the human factors and the human system while fully recognizing the limitations of M&S and the fluidity of the entity being modeled. A multidisciplinary approach to MHS M&S research and development fosters ongoing enhancement and improvement in the applications and tools available for the user community. As the MHS M&S toolbox expands and becomes more sophisticated, a *training environment with permission to fail* will yield both a desired *seamless mode of information transmission* and *proficient medical practitioners*.

MHS Research Centers

M&S is now an established research and development domain that is supported at all levels of government. In July 2007 the U.S. House of Representatives unanimously passed House Resolution 487, declaring M&S a *national critical technology* that can provide unparalleled advancements in American competitiveness, develop new and innovative ways to protect the homeland, and bring high-tech jobs and economic prosperity to our communities. Among the numerous descriptors found in the resolution is one specific to MHS: "acknowledges the significant impacts of M&S on a breadth of fields including defense, space, national disaster response, medicine, transportation, and construction." The same 2009 House and Senate resolutions that introduced *SIMULATION* (HR.855/S.616) focused further attention on the fact that M&S expertise would be needed at all levels: development, assessment (verification and validation), and usability.

From an engineering perspective, there is now, more than ever, a need for partnership between engineers and health care professionals; this is so if engineers as developers and medical professionals as users are to meet the six goals outlined by the Institute of Medicine in Washington, DC and its focus on *21st Century Health-Care*. The report by the institute calls for the health care system to be safe, effective, patient-centered, timely, efficient, and equitable. This is a challenge because the health care system is experiencing overwhelming advances and threatening declines. While the changes in medical technology and practice are advancing and improving training and patient care, shortages of skilled health care professionals are becoming severe.

Throughout the United States there are numerous institutes and centers whose research and development focus on *user* MHS M&S. The Advanced Initiatives in Medical Simulation—**AIMS**—is a coalition of professionals and organizations intent on promoting medical simulation to improve patient safety, reduce medical errors, train, and reduce health care costs. This collaborative body endeavors to engage the MHS M&S community, articulate a community-wide message to foster a uniform community, and secure resources necessary for future research and development. The Center for Integration of Medicine and Innovative Technology—**CIMIT**—is another leader in the MHS M&S community. Its aim is to initiate and accelerate translational medical research in the domain of devices, procedures, and clinical systems engineering. Harvard's Center for Medical Simulation—**CMS**—provides simulation training for health care providers through high-fidelity scenarios. (There are numerous other centers worthy of note, including Computer Aided Surgery, CAS; Image Sciences Institute, ISS; Computer Assisted Radiology and Surgery, CARS; and the Society in Europe of Simulation Applied to Medicine, SESAM.) Conversely, modeling and simulation research and development centers, such as the Virginia Modeling, Analysis, and Simulation Center—**VMASC**—also support various MHS M&S application areas and domains.

At VMASC, faculty among numerous disciplines (engineering, mathematics, health sciences, sciences) work in four areas of research and development: (1) training, (2) treatment, (3) disease modeling, and (4) management of health care systems. In the area of training, VMASC researchers developed a fully immersive virtual operating room outfitted with a simulated patient and both real and simulated instruments. In the domain of treatment, M&S is engaged for rehabilitation, to improve the diagnosis and treatment of orthopedic injuries and disorders, and to optimize physical performance. Mathematical models and computer simulations covering a variety of diseases are used for disease modeling. In the subset management of health care systems, researchers are using M&S to understand the effects of bioterrorism on the health care system in conjunction with a mass casualty model.

Meeting the growing demands of MHS M&S effectively and efficiently requires that the education of the M&S developer include explicit input from the user community—the MHS practitioner. A solid foundation for that type of education has its roots in a multidisciplinary approach: developers and users in the same classroom. As technology and application improve, simulation will no doubt find a permanent home in the MHSs. For many developers this is a grand accomplishment; for many users this is an opportunity to provide highly sophisticated patient care. But for some, these advancements give rise to the ethical question of using simulation, inanimate technology, to represent animate behavior and human systems.

THE QUESTION OF ETHICS IN MEDICAL AND HEALTH SCIENCES M&S

The advances made in computer capability (software, artificial intelligence, and software agents) facilitate the simulation of complex phenomena such as human behavior modeling and the modeling of human systems.† Modeling human systems encompasses the representation of the human body. This requires great technical skill, for with greater accuracy of human physiology comes higher-fidelity, more realistic simulation. For the most part, medical simulation is becoming an accepted methodology for educating future medical practitioners and for providing ongoing training and assessment for practicing professionals.

Juxtaposed with these technical advances is the ethical concern of representing human physiology via simulation. The concern emanates from academic disciplines that rely heavily on soft (or fuzzy) and evolving data such as the social sciences and medical and health sciences. Developers (both those producing the models and those creating the simulations) must address the credibility and ethical concern of modeling dynamic organic systems such as the human body to validate M&S as a MHS practitioners' tool. Central to the ethical discussion are the questions: Should computer models premised on mathematics represent human action (behavior) and human physiology (systems)? Is simulation a valid and verifiable means of characterizing humans? Discussing these questions proffers a means to bridge developer and user understanding of M&S. It also serves to communicate both the constraints and the potential of M&S.

The multidimensional capability of M&S credits it with being an enabling technology. As such, subfields of MHS make wide use of simulation, such as training with manikins, to using haptic devices, to imaging devices and virtual operating rooms.‡ There is a plethora of applications with promise of even more as medical simulation is used in multiple corners: research, evidence-based outcomes, medical education, and performance assessment, to name a few. In the MHS community medical simulation takes on the term **surrogacy**, which refers to the three modes of simulation in a clinical setting as human (a.k.a live), virtual, and mechanical (a.k.a constructive) [8]. Recall that human (live) simulation uses a trained role-player to act the part of a patient with a specific medical condition. This has been problematic in that a major limitation of human simulation is the inability of students to perform invasive procedures and other therapeutic interventions that could be harmful to the role-player. Virtual simulation employs the latest advances

†For a detailed history of medical simulation, see "Modeling and Simulation: Real World Examples—Medical" by C. Donald Combs, in *Principles of Modeling and Simulation: A Multidisciplinary Approach* edited by John A. Sokolowski and Catherine M. Banks, Wiley, Hoboken, NJ, 2009.

‡Human behavioral modeling allows for the incorporation of socially dependent aspects of behavior that occur when a member of people are together. Human behavior modeling is used in fields of study that include observations of human behavior, be they individual, group, or crowd.

in computer technology and visual interfaces to create acceptably realistic learning experiences.

Game-based medical simulation is proving to be an efficient and effective tool for teaching many clinical lessons without real patients and instructors. In **game-based learning** (GBL), realism is created in hybrid platforms that allow students to explore virtual environments with highly sophisticated mechanical interfaces. Additionally, there is *simulated vision* such as three-dimensional photorealism, which provides a sensation of realistic vision in virtual simulation. To create *simulated touch*, **haptic** devices are used to facilitate the sense of touch—students are able to feel what they are doing as well as to see it. This teaches the student how to gauge pressure application. Mechanical (constructive) simulation allows students to use mock or artificial parts to mimic the experience that would typically be gained from interacting with a real patient's body, organs, or tissues. In **augmented reality**, an application of integrated technology simulation is used to enhance real therapeutic interventions. Those endorsing augmented reality believe that *reality plus simulation produces a better outcome than reality alone*. Still, professionals in the MHS view the implied trade-off between reality and simulation as insufficient proof that one is superior to the other [8]. So what role should simulation play in MHS?

In 2001, a simulation gaming symposium drafted an assessment of the current state of affairs in MHS M&S [9]. Included was the general concurrence that the bridges between medicine and simulation are many and varied. Coupled with that is the fact that medical simulation itself is in overlapping areas of medicine and health care. Practitioners across the large domain of health care for the most part consider medical simulation beneficial. They contend that as the population increases, awareness of health issues improves, society continues to age, and MHS research and development progresses, health care demands will increase exponentially. Thus, the symposium came to what it believed to be a logical conclusion: There is a need to exploit the benefits of simulation in both training and operation.

Pedagogically, many institutions are using M&S training tools specific to MHS. This is due to the fact there is a great need for doctors and health care providers to quickly gain and maintain competence and demonstrate proficiency in the use of these new technologies. Consider the following:

- It is predicted that by 2020 there will be a 20% shortage of nurses.
- Medical residents training or operating within an 80-hour workweek have less opportunity to interact with instructors.
- It is estimated that deaths from medical errors range from 44,000 to 98,000 annually, with 1 million injuries attributed to medical error.
- Various threats (such as bioterrorism) call attention to the speed needed to train first responders (EMS personnel) to react to health crises.

One can speculate as to why these numbers are so high: lack of adequate training, overworked personnel, inadequate tools, and insufficient staffing, among others. A proponent of simulation training, S. B. Issenberg (Center for Research in Medical Education, University of Miami School of Medicine), has suggested a framework for thinking about how to use medical simulators. Issenberg emphasizes the use of repetition, measurement of performance, and feedback as a way to strengthen and to standardize important components of medical education [10]. Health care educational institutions are also aware of the need to provide students with simulated experiences that will enhance educational experience and improve patient safety [11].† Still, this type of education and training is not without its critics, who raise questions of validity and ethics.

For example, there are numerous potential applications of simulation for the assessment of clinical competence; however, that use has not been widely supported within the health care community [11]. Concerns about the use of simulation to performance assessment include competing tensions between dual goals: One goal is to achieve high reliability and the other goal is to achieve high validity. The concern is that these goals appear to require mutually exclusive test conditions. Still, experimental studies have demonstrated that moderate levels of reliability and validity can be achieved simultaneously with manikin simulations if test conditions are managed appropriately.

Other critics of simulation use have made the case that simulation not be used in isolation to make a determination about a practitioner's overall performance; rather, it should be incorporated into a broader, multifaceted program [11]. There are also high-stakes performance assessments. These assessments refer to those that lead to an overall judgment about a previously qualified practitioner's professional performance, for the purpose of renewing practice privileges. These high-stakes performance assessments may involve standardized screening exercises for routine recertification, or they can be a tailored exercise. Proponents of this application make the case that it is beneficial to do this in a simulated environment because using real patients is considered unethical, there are not enough patients available for these exercises, and there are not enough cases to provide realistic patient variability [11]. Training with cadavers and laboratory animals is challenging. Cadavers have the correct anatomy; however, they are expensive, sometimes difficult to procure, and suffer tissue degradation. Animals pose a challenge as well: They do not have the same anatomy, can be expensive, and are not reusable. (There is also an ethical question regarding the use of both cadavers and animals in medical training, such as that expressed by PETA, People for

†Haptic technology serves as the interface within a simulated environment, engaging the user's sense of touch by applying forces, vibrations, and/or motions to the user.

Ethical Treatment of Animals.) For health care educators, simulations allow the practice of safety, prevention, containment, treatment, and procedure in a risk-free setting [7].

Simulation provides a method enveloping both training and feedback in which students can practice a task in lifelike circumstances using models or virtual reality with an opportunity to gather feedback; this, in turn, allows students to practice and review as often as required to attain the desired level of proficiency. Arguing for the integration of simulation in MHS education, McGaghie, et al. [12] refute some of the issues presented by critic Geoffrey Norman, editor of *Advances in Health Sciences Education* [13]. Norman listed seven issues, ranging from the lack of a common platform for sharing, due to the fact that the discipline is so new; the fact that the training outcomes in using real patients and simulated tools are only slightly better; and the fact that the costs of high-fidelity simulations limit which schools can afford them.

Richard M. Satava of the University of Washington has also supported the use of simulation in MHS education. Satava considers simulation an appropriate medical educational tool. His conclusion coincides with the Residency Review Committee of the Accreditation Council on Graduate Medical Education, which has begun requiring residency programs to have simulation as an integral part of their training programs. The American College of Surgeons (ACS) is also making use of the tool and is certifying training centers to ensure the quality of training provided. Satava suggests that the by-product of simulation use in health care education will be standardized curricula [7].[†] As such, simulation-based medical education (SBME) has been expanding its tools and approaches to include task trainers, simulated patients, computer-based training, and full-environment simulators.

That *permission to fail* (as described by Satava) learning environment is also an evidence-based learning environment [7]. This is because simulation allows for anything that reproduces experimental, clinical, or educational data. Still, one must be careful to note the difference between the model and the simulation. Herein lies the ethical and validity question because *a simulation is no better than the model it engages*. Also, the model is arguably the most important part of the simulation, as it constrains the simulation from being a false representative. Thus, clinical simulators need a model to drive them, and that model development is called into question if and when the

[†]For a discussion on simulation use in surgical education, see “Support for Simulation-Based Surgical Education Through American College of Surgeons: Accredited Education Institutes,” by A. K. Sachdeva, C. A. Pellegrini, and K. A. Johnson in *World Journal of Surgery* (2008) 32:196–207, DOI 10.1007/s00268-007-9306-x. As of 2008, the American College of Surgeons certification requires three categories of students who are to be taught using simulation.

user is doing the modeling, especially if the user is not a trained modeler. This is a concern, because what one sees in the simulator is what the model produced. Simply, if the physiology (the model) isn't realistic, the simulation isn't realistic.

To address this concern, simulations must be able to pass the **Turing test**, which means that under a variety of circumstances there is no discernible difference between the output of the model in a simulation and the true condition of real patient [14].[†] Thus, a clinical simulator should have an accurate physiological model as its engine. This is necessary because a failed Turing test can teach inaccurate information to students. Also acknowledged is the fact (or engineering constraint) that even the best model is a compromise, as not every detail can be included. *Model compromise* is an art, and those constructing models for clinical simulation should have detailed knowledge of physiology, pharmacology, toxicology, and clinical realism [7]. Unfortunately, this has not always been the case, leading some users to disavow the use of simulation.

The prevalent philosophy in medical ethics emanates from two perspectives: beneficence and nonmaleficence [3]. **Beneficence** speaks to the provision of benefits, whereas **nonmaleficence** centers on the avoidance of doing harm. Traditionally, the ethics of medical care has given greater prominence to nonmaleficence than to beneficence; however, the advent of modern science is changing that. The practice of medicine has long been dictated by the use of knowledge acquired in labs, tested in clinics, and verified by statistical methods. For many, the rapid advances in medical technology, including simulation, have produced great uncertainty as to *what is beneficial* and *what is least harmful*. In the article "Ethical Issues in the Application of Virtual Reality to Medicine," Whalley suggested that virtual reality training would lead to placing patients in virtual environments [15]. The concern at the time of his writing was that the research would be ahead of the interests of the

[†]The Turing test is an informal validation method well suited to validating models of human behavior, first proposed as a means to evaluate the intelligence of a computer system. As conventionally formulated, a computer system is said to be intelligent if an observer cannot reliably distinguish between system- and human-generated behavior at a rate better than chance. When applied to the validation of human behavior models, the model is said to have passed the Turing Test and to be valid if expert observers cannot reliably distinguish between model- and human-generated behavior. Because the characteristic of the system-generated behavior being assessed is its degree of indistinguishability from human-generated behavior, this test is clearly directly relevant to the assessment of the realism of algorithmically generated behavior, perhaps even more so than to intelligence, as Turing originally proposed. For more information, see "Verification and Validation" by Mikel D. Petty, in *Principles of Modeling and Simulation: A Multidisciplinary Approach* edited by John A. Sokolowski and Catherine M. Banks, Wiley, Hoboken, NJ, 2009.

patient, and that the technology could be prone to error that would introduce specific distortions. But simulation has moved forward and has made great strides in creating human representations and environments that have addressed those distortions. As a result, M&S is becoming an acceptable part of medical training.

Despite having its critics, simulation is at the center of classroom instruction as a result of the confluence of technological advancement and the dire shortages of trained personnel in the health care field. Teaching programs have seen numerous unfilled faculty positions because health professionals with advanced training (the pool of eligible educators) can earn more in clinical practice. Additionally, the practice of hands-on training in the health professions may not be sustainable as the predominant model for preparing health professionals [8]. Thus, simulation-based training may be the sensible and most efficient method of avoiding dangerous shortages of caregivers. Advocates of simulation in health care education view simulation as *augmenting training*; they contend that simulation does not need to provide a perfect representation of a real medical problem as long as the approximation of reality produces the educational outcome desired. The supporters of simulation-based training conclude that the effectiveness of simulation training is judged by how well students learn the relevant lessons and skills, not how well the simulation resembles a human being with a medical problem [8].

At the Center of the Question . . .

At the center of the ethical concerns about simulation in the MHS are the three key actors: the at-large community of ***modelers***, who select (or are given) data and make assumptions as to the content and characterization of the model; the ***simulationists***, who design the experiment (or training scenario); and the ***analysts***, who interpret the results of the simulation. It is important to note that the modeler is dependent on data to develop his or her model and that the best data in any model design come from subject matter experts. Thus, models representing human behavior, such as decision making or human interaction, rely on the qualitative analysis of subject matter experts who study human behavior, such as social scientists. Representing human systems requires expertise in the study of the anatomy from those among the MHSs.

Simulationists need to know the parameters and capability of a model for the creation of an experiment. Thus, a simulationist's skill set should include an understanding of modeling with subject matter expertise. Analysts (who are often the users) interpret the results of the simulation and make use of it in prescribing a response. Analysts should have subject matter expertise as well as an understanding of how the model was developed, including its design, intent, and limitations. Critical to model creation and simulation development is the ability to obtain dependable results. Therein lies the crux of the ethical issue in representing human behavior and human systems—the development of techniques to firm-up soft data and the representation of those data.

In the article "Models, Measurement, and Computer Simulation: The Changing Face of Experimentation," Margaret Morrison argues that computer simulations have the same epistemic status as experimental measurement when looking at the role that models play in experimental activity, particularly measurement [16]. Morrison attributes *models as measuring instruments* and *simulation as the experimental activities*. A model can be based on some theoretical belief about the world that is suggested by the data, or it can sometimes be understood as simply a statistical summary of a data set. With that, data assimilation is an example that extends beyond straightforward issues of description, and models fill the gaps in observational data. Again, there is an emphasis on the need to represent soft data accurately because the knowledge associated with the measurement comes via the model [16]. Moving to the next step, simulation development, Gilbert and Troitzsch suggest that the major difference between simulation and experiment is that in the latter, one is controlling the actual object of interest, whereas in a simulation, one is experimenting with a model rather than with the phenomenon itself. They contend that computer simulation is similar to experimentation in that it starts with a mathematical model of the target system and application of discretizing approximations, which replaces continuous variables and differential equations with values and algebraic equations [17].

There is a school of thought that adheres to the principle that *models mediate between us and the world* and *between us and theories* by acting as objects of inquiry and the source of mediated knowledge of physical phenomena. This mediated knowledge is characteristic of the type of knowledge acquired in measurement contexts. Morrison contends that the connection between models and measurement is what provides the basis for treating certain types of simulation outputs as epistemically (cognitively) on a par with experimental measurements. As such, computer simulation enables representation of the evolution of a system to measure the values of specific properties as the system approaches a critical point [16].

There is also the question of *complicated systems versus complex systems.* How do they differ? These systems diverge based on the level of understanding of the system; for examples, a human system may have few parts, but it is complex because it is difficult to ascertain absolutes in the data, as human systems data are organic and dynamic. Thus, one cannot predict the behavior of a human system with any certainty. On the other hand, a finite element model or physics-based model may be complicated, due to its numerous parts, but it is not complex, in that it is predictable and because the data to model such a system are not soft data.

Modeling human systems is also challenging. Still, it is becoming more and more necessary in light of the need to use simulation to train health care providers, due to the known and predicted shortages in the health care community. As discussed above, the MHSs are making greater use of simulation for training and patient care. Simulation training tools enable health care professionals to sharpen their assessment and decision-making skills without risk to patients in realistic, challenging, immersive environments that are instrumented to provide meaningful performance feedback. Some simulation tools facilitate training-to-proficiency in error-prone tasks. There are also manikins that simulate breathing, exhibit pulse and mimic vital signs, and respond to treatment. This type of training accelerates traditional training methods of watching procedures, then practicing what has been observed. Advances in technology have introduced training environments that go beyond simply simulating the vital signs; in fact, some are capable of representing every orifice as naturally as possible, with the ability to spurt blood and mimic the effects of biological attacks. Researchers have also developed better representations of skin, blood, and bone so that wounds have the correct smell, feel, and physiological accuracy. Amazingly, these advances have come without the benefit of a closer relationship between the developer and user communities.

CONCLUSION

In this chapter we have introduced the fundamentals of M&S in the medical and health sciences, such as the modes of M&S (live, virtual, and constructive), to conceptual model design and the evolution of model development as a mathematical or physical representation. We also highlighted the various roles, uses, and needs of the developer and user populations. With a model in hand, simulation is introduced; and it is used to facilitate the reproduction of experimental, clinical, or educational data.

We drew attention to the need for a more uniform dialogue of simulation within and between the M&S engineering and M&S medical and health sciences domains. As such, the information is presented with these two student bodies in mind, to enlighten them as to what they are required to master so that they can dialogue and collaborate with an informed understanding.

A strong case endorsing the use of M&S in education and training is being made across institutions and research centers—the sheer need for a larger body of health care professionals leads that discussion. Still, there are some who question the credibility of M&S in this domain. An intriguing seminal piece entitled "Posthuman Future: Consequences of the Biotechnology Revolution," by Francis Fukuyama (Paul H. Nitze School of Advanced International Studies, Johns Hopkins University) cautions against blindly wielding the new tools that science creates. Fukuyama counsels developers and users to consider carefully each step taken in the name of health progress, and to guide the medical community with intelligent debate on the consequences of human intervention [6]. We acknowledge his concerns.

To mitigate the *blind wielding* of these new tools, in this chapter and the ensuing discussion in Chapters 2 through 10 we endeavor to build that much needed two-directional bridge where medicine meets virtual reality (a.k.a. modeling and simulation) and where modeling and simulation meets medicine.

KEY TERMS

clinical engineer	constructive mode	CIMIT
biomedical engineer	computational model	CMS
engineered device	physical model	VMASC
biomechatronics	humans as models	surrogacy
robotics	human systems modeling	game-based learning
training simulation		haptic device
analysis	disease modeling	augmented reality
experimentation	virtual operating room	beneficence
training	standardized patient	nonmaleficence
modes of M&S	modified stethoscope	modeler
live mode	science of simulation	simulationist
virtual mode	AIMS	analyst

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