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Transforming Education through Emerging Technologies
Research Synthesis Paper

Emerging technologies in medical education:

The role of simulation in bridging the divide between knowledge acquisition and application and better preparing medical students to be effective physicians

Introduction

In 1910, Abraham Flexner published a report on the state of medical education in the United States and Canada. His eponymous report criticized medical schools for their lack of rigorous academic standards, poor understanding of science, and for generally contributing to the common public conception of physicians as “quacks” (Flexner, Carnegie Foundation for the Advancement of Teaching., and Pritchett 1910). His report had many consequences for medical education, including the move toward a four-year medical school model and a new focus on understanding the “how” of medicine—the physiology underlying the internal processes of the human body.

The Flexner Report was published more than 100 years ago yet still the current structure and focus of medical education. Students spend their first two years in pre-clinical courses, learning in lectures and from textbooks about topics like anatomy, genetics, biochemistry, and human physiology and pathophysiology (emphasizing knowledge acquisition). In their final two years, students practice clinical medicine in the hospitals, applying their book knowledge to caring for human patients (emphasizing knowledge application).

The Problem of Knowledge Acquisition vs. Application in Medical Education

The pre-clinical and clinical years of medical school require vastly different skills to be successful. During the pre-clinical years, students work individually to memorize vast quantities of information, ranging from the specific enzymes involved in replicating DNA to the mechanism by which blood pressure medications work. Much of the information learned (such as the steps of DNA replication) will be largely irrelevant to the practice of clinical medicine. In contrast, during the clinical years, students must become adept at interacting with and caring for patients, working in teams, and applying knowledge to clinical scenarios. It is not enough for a clinical student to know how various blood pressure medications work—she must also be able to apply this knowledge and select which type of medication is most appropriate for a particular patient. Then using patient-appropriate language, she must discuss the medication, its indications, and possible side effects with the patient. These skills are crucial to being a successful practitioner of medicine but not emphasized during the first years of medical school.

Unfortunately, medical schools rarely focus on helping students bridge the transition between these two spaces. There is often a “sink or swim” mentality to beginning clinical rotations. Many successful pre-clinical students find it difficult to apply their knowledge to patients or lack the empathy necessary to be successful clinical practitioners. Conversely, many successful clinical students lack motivation and purpose in their pre-clinical years, where it is often difficult to see the connection between a multiple choice test and caring for patients.

A real question facing medical education is how to engage students in their pre-clinical years and ensure that they are adequately prepared for the transition to clinical medicine. How can we ensure that the skills required to be a successful clinical student are being developed during the pre-clinical years? How can we ensure that knowledge acquisition and application are occurring simultaneously throughout medical school and not separated by the dichotomous structure of current medical school education?

Description of the Emerging Technology

Over the past several decades, the introduction and improvement of medical simulation technology offers the potential to merge knowledge acquisition and application in an engaging environment through hands-on experience. Medical simulation is a broad term that encompasses many different categories of simulation, including verbal, standardized patients (SPs), computer patients, part-task trainers, and electronic patients (Rosen 2008). Verbal simulation is simple role playing, and standardized patients are actors that play patients in simulated patient encounters (a more realistic type of role playing). Because there is little technology involved in these categories of simulation, I will not include them in the discussion that follows. Computer patients are interactive and generally software-based, serving a role similar to standardized patients at reduced cost (Rosen 2008). Part-task trainers are often static anatomical models designed to help teach a particular skill, such as intubation; however, this category also includes complex virtual reality-based surgical simulators. Electronic patients comprise physical mannequins that stand in for humans, with palpable pulses, measurable blood pressure, and organ systems that portray physical exam findings (such as heart murmurs). Well-positioned speakers enable these mannequin-patients to "talk," and software enables their bodies to physiologically respond to interventions, like giving intravenous fluids or administering medications.

Although there is significant value to each category of medical simulation, the following discussion will focus on the more advanced part-task trainers and electronic patients. This is because they best represent the intersection of technology and clinical medicine and are therefore best able to provide meaningful clinical-like scenarios to students during their pre-clinical years. Moreover, it is these two categories of simulation that remain "emerging." The earliest part-task trainer was designed in the 1960s. Called Resusci Anne (Figure 1), the model included a woman's head and upper torso and was used to practice mouth-to-mouth breathing (Rosen 2008). Although simulation technology progressed steadily over the next several decades, it was not until the late 1990s and early 2000s that computer technology had developed enough to enable high quality virtual reality-based surgical simulators and the physiologically responsive simulation mannequins on which this paper will focus. Indeed, high fidelity simulators have been around for only the last 10-15 years and are being continually improved even today.

Potential Learning Outcomes of Medical Simulation

The ultimate goal of simulation-based medical education (SBME) is to improve patient outcomes through better training of medical practitioners. Medical simulation provides clinical experiences without risk to human patients, even allowing trainees to practice handling situations that may one day mean the difference between life and death for a human patient. Similarly, it offers medical students the chance to start developing the skills and comfort required in clinical encounters before they enter the hospital wards, such as how to care for a patient who cannot answer questions, how to effectively work as a team, and also practical skills like how to intubate a patient. By reducing the time it takes students to adjust to the wards, SBME actually maximizes the time they can spend learning medicine. Of course, it also helps that students and trainees generally find simulation sessions engaging and enjoyable.

Analysis of whether the impact is conventional or transformational

Beyond considering whether or not an emerging technology can address problems in medical education, it is important to consider whether that impact will be conventional or transformational. *Conventional* technology is used to "do conventional things better," whereas *transformational* technology is used to "do better things," such as better preparing students to confront the challenges of the real world (Dede In press). It is important to consider that whether a technology is transformational depends on the context in which it is used, including whether instructors have been adequately trained in use of the technology and how it is integrated into the curriculum (Dede In press). Therefore, although a technology may have the potential to be transformational, when used without the necessary support and context, it may have no more than a conventional impact.

SBME certainly has the capacity to be a transformational technology. As discussed above, electronic patient encounters foster teamwork, support hands-on skill building, and provide an environment in which to practice applying knowledge to patient encounters. They prepare medical students to function at higher levels in real world clinical encounters. Moreover, SBME reduces the amount of patient harm that occurs in medicine. For example, a student who has practiced proper intubation technique on a mannequin will be better prepared to intubate a live patient, including less likely to make mistakes like putting the breathing tube down the esophagus instead of the trachea or chipping teeth. (It is important to realize that the amount of harm in medicine can never be zero, since trainees—students, residents, and fellows—will always make mistakes. The amount of harm is mitigated by close supervision and intervention of attending physicians in necessary circumstances.) Without a doubt, protecting patients from unnecessary harm falls under the category of "doing better things" implicit in transformative use of a technology.

Unfortunately, SBME is not always utilized in a transformational way. The quality of the experience students have in simulation sessions significantly depends on the instructor, who acts as the patient, ensures a medically realistic scenario, and runs a debrief session after the simulation experience is over to highlight important concepts and skills. Although many simulation instructors have been specifically trained in running simulations to maximize learning, there can be variability. Perhaps what most limits the transformative impact of medical simulation technology is the superficial way in which it is integrated into medical schools. Instead of forming a consistent part of medical school curricula, simulation is offered as a "fun" but rare experience. Students cannot become adept at working in teams or learning how to apply factual knowledge to clinical scenarios if they are given this opportunity only a few times a year.

Some medical schools (including at my school, Harvard Medical School) offer weekly extracurricular simulation experiences that enables more transformative use; however, the onus remains on the student to seek this out.

Overview for Remainder of Paper

The remainder of this paper will analyze the effectiveness of medical simulation technology at preparing pre-clinical students for clinical responsibilities, as well as promoting both knowledge acquisition *and* application in the early years of medical school. This analysis will include a discussion of how SBME incorporates tenets of adult learning theory and other theoretical learning frameworks, whether the empirical evidence supports its use in medical education, the strengths and limits of the technology, and a description of my own personal experiences with it.

Theoretical and Empirical Framework

Theoretical Frameworks

The theory of teaching and learning best exemplified by medical simulation technology is Malcolm Knowles' theory of andragogy. Andragogy was born out of Knowles' interest in adult learning theory and based on a belief that adults are self-directed learners and expect to play a role in their own education. Andragogy describes effective adult learning as 1) experiential, 2) personally relevant, 3) problem-centered instead of content-oriented, and 4) self-directed (Knowles 1970). Whether purposeful or not, SBME incorporates all four of these principles.

Medical simulation scenarios are as experiential as medical education can get without involving real patients. Students practice taking history and physical exam skills with a patient, creating a differential diagnosis of the patient's problem when pressed for time, and treating the patient through various interventions, such as administering drugs or performing CPR. Instead of reading about the steps of CPR in a book, students must practice distributing team roles, performing chest compressions, and deciding what medications to administer. The situation leaves no time to look up notes taken in a lecture—make mistakes and the electronic patient will "die." It is this experiential aspect of simulation that drives home how real the situations will be in just a couple years—making the personal relevance to students exceedingly clear. Although medical simulation requires content knowledge upon which to build, scenarios themselves are focused on addressing problems in clinical medicine, such as how to manage a patient that is not breathing or to care for a child with a severe asthma exacerbation. Simulation helps teach students how to solve the problems they will soon encounter on the wards. SBME also allows students to direct their own learning, even when the simulation case has already been chosen. Instructors do not intervene during the active simulation, so students make every decision during the case. How the electronic patient responds to an intervention (i.e. getting sicker or better) provides a natural feedback mechanism to help students understand whether the intervention was appropriate. Different groups of students will choose different interventions; the education students receive therefore depends specifically on the direction they take in the scenario. At the end of the session, instructors can further highlight specific educational goals as needed.

We can contrast SBME to traditional lecture-based instruction with respect to andragogical principles. Although a lecture on congestive heart failure is generally relevant to what medical students will need to know, it has no experiential component, is generally content-oriented, and is not self-directed—a professor decides what content will be conveyed. Of course, traditional lectures and book learning are absolutely an important part of medical education. Students cannot apply knowledge that they have not first acquired. However, SBME does provide an important opportunity to complement traditional learning formats in medical school through its adherence to andragogical principles that ensures students maximize their learning.

Beyond understanding how andragogy relates to medical simulation, another important consideration is what theories of teaching and learning can help guide the planning and structure of simulation experiences. In particular, cognitive load theory (CLT) plays a crucial role in maximizing learning potential with medical simulation. Developed by John Sweller, CLT tries to align learning with human cognitive architecture. Essentially, short-term memory ("working memory") is limited in its ability to process novel information; when too much novel information is presented, the "cognitive load" surpasses working memory's capacity and learning is impaired (Sweller 1988). In fact, there is empirical evidence that cognitive load does impact learning from medical simulation. In one study, first year medical students were trained using simulation on chest pain caused by aortic stenosis, a valvular condition of the heart that produces a heart murmur. Students rated the "amount of mental effort required" for the scenario (a stand in for cognitive load), and were then asked to identify two heart murmurs—one from aortic stenosis and one associated with an unfamiliar condition. The study found that students who rated a higher cognitive load were less likely to correctly identify either murmur (Fraser et al. 2012), suggesting that high cognitive load impaired learning. CLT therefore aims to minimize cognitive load when learning new information in order to maximize its transfer from working memory to long-term memory.

There are several ways in which CLT can enhance medical simulation. Cognitive load can be intrinsic (related to the complexity of the material) or extraneous (related to poor instructional design). Some of the intrinsic cognitive load associated with medical simulation comes from inexperience with simulation environments. For example, students may be unfamiliar with the information displayed on bedside monitors or the specifics of the mannequin, such as where to listen for lung sounds or if the pupils react. When they begin a simulation session, the time and effort they put into familiarizing themselves with the monitors and mannequins increases cognitive load and detracts from the patient encounter, decreasing the effectiveness of SBME (Fraser, Ayres, and Sweller 2015). One solution to this is “pre-training,” in which instructors provide a briefing of the clinical/simulation environment, review what information can be obtained from the mannequin, and clarify what tasks students must complete without help from a “nurse” (such as phlebotomy). Lack of student clinical knowledge can also contribute to intrinsic cognitive load. For example, a student may correctly identify that a patient’s problem is related to the heart and request an electrocardiogram (EKG) without being able to understand what the EKG shows. In such a situation, scaffolding—broadly meaning any type of guidance given to a learner—is a crucial tool to reduce the cognitive load of learners (Fraser, Ayres, and Sweller 2015). Instead of struggling to try to read the EKG for the patient, students could call a cardiology “consult,” in which the instructor briefly explains the EKG findings. The students can then proceed with the scenario, perhaps circling back to the EKG interpretation during the debrief session.

An important aspect of the extraneous cognitive load associated with medical simulation comes from the split-attention effect, which occurs when learners divide their attention between multiple sources of information (Fraser, Ayres, and Sweller 2015). For novice learners such as early pre-clinical students, trying to integrate information obtained from the patient, the nurse, and the laboratory may be overwhelming. It may be more effective to provide a single source of information, such as a paper document containing the history, physical exam findings, and laboratory values. As learners develop familiarity with simulation over time, their working memory has more space to process complex environments, at which point diversifying the sources of information can help students improve their skill at integrating clinical information.

Both andragogy and cognitive load theory are fundamental to understanding why and how medical simulation *can* be an effective learning tool, including how it can help pre-clinical medical students prepare for clinical medicine. However, it is also necessary to consider whether it *is* an effective learning tool, which requires an examination of the published literature.

Empirical Frameworks

Although SBME can be evaluated in many different ways, this paper will focus on quantitative and qualitative measures applicable to preparing pre-clinical students to be effective clinical students and future medical practitioners. In particular, this requires students to acquire skills and knowledge and transfer that knowledge to practice.

One of the more common objectives of SBME is acquiring clinical skills. Simulation is frequently used to teach procedural skills, but it can also be used to develop professionalism and communication skills among patients. In 2011, a meta-analysis encompassing 609 studies and more than 35,000 trainees was performed to determine the effectiveness of simulation based education. This analysis found that compared to traditional instruction methods, SBME was associated with large gains in knowledge (improved multiple-choice test scores), product skills (such as quality of a dental preparation), process skills (global ratings of performance by instructors), and behaviors (such as time management) (Cook et al. 2011). In most circumstances, these evaluations occurred while trainees were in simulation environments and not true clinical environments. Therefore, these measures were specific for skill acquisition and not related to transfer to practice. Given the recent nature of this study, the enormous amount of trainees included in the analysis, and its rigorous methodology, the study's conclusion that SBME is effective at helping students acquire skills and knowledge is convincing.

To provide a more concrete example—one example of a study included in Cook's meta-analysis examined whether simulation training improved cardiac auscultation skills in medical students. Students who had received one hour of a computer-based auscultation tutorial were compared to older students who had not received this training although had more clinical experience. All students were asked to complete a computer-based multiple-choice assessment of simulated heart sounds. Students who had undergone simulation training demonstrated higher accuracy in identifying the sounds (93.8% vs. 73.9%, $p<.001$), suggesting SBME helped students acquire important clinical skills (Butter et al. 2010).

Although the meta-analysis found SBME effective on skill-based metrics, other researchers have cautioned that the benefits of simulation training are generally small, on the order of <3% increase in clinical skill (Teteris et al. 2012). Moreover, the outcomes of these studies are difficult to measure without bias. For example, often skill assessment occurs on the simulator following training, which favors students who received the intervention, since they are more familiar with the evaluation format (Teteris et al. 2012).

When considered as a whole, the evidence does appear to support SBME as an effective method through which medical students can acquire clinical skills and knowledge, which should better prepare them for the transition to the wards. In other words, we are interested in how well skills learned in simulation *transfer* to clinical practice and further, whether patient outcomes improve when trainees have simulation experience.

The published literature also supports that SBME promotes transfer of skills to clinical practice. Cook's meta-analysis found that medical simulation was associated with moderate gains in patient outcomes in many different settings and medical specialties (Cook et al. 2011). To consider some specific examples, one retrospective case-control study in 2004 found that simulation-trained residents better adhered to American Heart Association guidelines for providing advanced cardiac life support to patients (66% vs. 44%, $p=.001$) (Wayne et al. 2008). In the field of surgery, a randomized controlled trial found that residents who had been trained on a virtual reality surgical trainer had better operating room performance than residents who did not undergo simulation training. Simulation-trained residents performed laparoscopic gallbladder removal 29% faster and were less likely to injure the gallbladder or burn surrounding tissue ($p<.05$) (Seymour et al. 2002). In obstetrics, a study examined whether providers who underwent simulation training on managing shoulder dystocia, a potential neonatal complication of vaginal delivery, had better neonatal outcomes. The study found that neonatal injury was significantly reduced after simulation training was implemented (9.3% vs. 2.3%, $p<.05$) (Draycott et al. 2008). All of these studies suggest that students who have undergone simulation training perform better during clinical encounters; ultimately, that improved performance leads to better patient outcomes. A causal relationship between simulation and improved patient outcomes is suggested by the fact that at least one of the studies was a randomized controlled trial. Although the other studies were observational or case-control, the significant similarities between simulator-trained participants and their untrained controls also support a causal relationship, since there are few measures besides simulation training on which subjects differ.

Evaluation of the Claims Made by Advocates of SBME

To date, the data supports advocates' claim that SBME is an effective tool through which students can both acquire knowledge and learn how to apply that knowledge in the clinical world, even improving patient outcomes. It is fitting then that the slogan of Laerdal Medical

Corp., the company that created Resusci Anne and one of the leading producers of electronic patients today, is “helping save lives” (Laerdal. 2015).

However, advocates make several other claims about the benefits of simulation that are not as well supported by the literature. For example, the assertion that simulation improves skill training and patient outcomes implies that it fosters skills crucial to clinical medicine. This is not always the case. One study found that fourth-year medical students who had undergone extra simulation-based teaching in anesthesia were more confident in their skills compared to a control group of students; however, there was no statistically significant difference between the two groups’ scores (Wenk et al. 2009). In other words, simulation training can cause overconfidence in medical students. When such students enter the wards, they may overestimate their abilities and seek out situations for which they are not qualified; this can be a source of medical errors and cause harm to patients.

Advocates also claim that despite its costs, SBME can be a cost-effective addition to medical education. Costs for the various types of medical simulation technology vary widely; Laerdal’s SimMan 3G, its top-of-the-line mannequin, costs around $75,000, which does not include maintenance costs (Laerdal. 2014). However, if SBME enhances diagnostic skills, it may reduce the need for diagnostic tests, which can cost upwards of thousands of dollars, thereby saving money in the healthcare system (Issenberg et al. 1999). Unfortunately, there is no evidence supporting this claim (unsurprisingly, as it would be exceedingly difficult to devise a study that linked decreased healthcare costs to SBME).

As medical simulation technology continues to advance, there is a push for greater “fidelity” to human patients. Once sufficient for instructors to convey physical exam findings (“the patient’s eyes are tearing”), now there is a desire for mannequins to actually produce eye secretions. While instructors once manually entered physiologic responses to administered medications (such as increase in HR, decrease in BP), now the software for electronic patients can do this automatically, even varying responses based on the amount of drug given and how quickly it is administered. The graphics of high-end virtual reality surgical trainers mirror reality, but there is a continuing effort to develop the technology that will incorporate touch and tissue feedback to these trainers. This attitude makes a lot of sense—if one of the benefits of SBME is to mimic clinical environments, then surely the closer to reality the greater the benefits. Surprisingly the data suggests otherwise. While both high-fidelity simulation (HFS) and low-fidelity simulation (LFS) improve trainee skills and transfer compared to no simulation, there is no significant benefit to HFS over LFS (Norman et al). For example, in one study, residents were taught ureteroscopy (inserting a camera into the ureters through the bladder) with a didactic session, a coffee cup and straws (LFS model), or a commercially available simulator (HFS) and then assessed. While both simulation methods were superior to the didactic session, there was no difference between the skills of learners in the LFS and HFS groups (Matsumoto et al. 2002). Interestingly, if LFS is equivalent to HFS, then effective medical simulation may be more cost-effective than previously thought.

Strengths and Limits of the Technology for Education

As discussed in the previous sections, there are many strengths and limits to the educational use of medical simulation, much of which is supported by anecdotal and empirical evidence. Known advantages of SBME include its compatibility with adult learning theories like andragogy and cognitive load theory, the provision of a safe environment for training that does not expose patients to risk, an opportunity to practice clinical skills including effective teamwork, and improved patient outcomes. Known disadvantages of SBME include costs, learner attitudes such as overconfidence, and variable infrastructure and curricular integration supporting the technology depending on the institution (McFetrich 2006).

Beyond the known strengths and limits of SBME, others remain to be discovered. Perhaps the most interesting opportunity for medical simulation is within the field of assessment. Because simulation scenarios can be standardized (same patient history, physical exam findings, vital signs, etc.), it has the potential to assess trainee competency, such as whether pre-clinical students are prepared to care for patients on the wards. Others have pushed for simulation to supplement current medical licensure requirements, which tend to be multiple choice or oral exams and therefore poor indicators of true clinical performance. Indeed, the idea of simulation as an assessment tool to measure clinical competence has been around for nearly twenty years (Gaba et al. 1998). Unfortunately, concerns over developing appropriate test scenarios, scripting all the possible “correct” routes a scenario could take, and reproducing these scenarios exactly for all potential candidates has proved onerous (Kapur and Steadman 1998). The usefulness of medical simulation in formal evaluation and assessment thus requires further investigation.

Another question that remains to be answered is how frequent simulation must be to have a lasting impact. One systematic review examined the aspects of medical simulation required to maximize learning, and nearly forty percent of the articles in the review identified “repetitive practice” as a key feature when using simulation (Issenberg et al. 2005). This review found that repetition allowed students to acquire skills in shorter time periods and improved knowledge transfer from simulators to patient care. However, no study has determined what constitutes the minimum required repetitive practice (Two sessions? Ten sessions? Weekly sessions?). How integrated and frequent does medical simulation need to be to be a transformative technology for students? The answer to this question is not currently known.

Personal Experiences with Medical Simulation

As a Harvard Medical School (HMS) student, I have had firsthand experience with medical simulation scenarios, as have my classmates. Indeed, much of my interest in researching medical simulation for this paper was due to my personal experiences (Figures 2-3).

At HMS, there are three different times in which students have the opportunity to engage in simulation-based education. In the first week of school, students attended one to two scenarios as an introduction to medical school and a primer on medical simulation. During required preclinical courses over the first two years, students have six to seven simulation experiences during which they must apply knowledge from a course (such as cardiology) to a scenario (such as a patient presenting in congestive heart failure). Finally, there are extracurricular simulation sessions over the first two years, of which about 100/165 HMS students take part (Gordon Nov 5, 2015.). Students who do extracurricular simulation are split into groups of about five students and spend one hour doing a simulation scenario and debrief every other week over two years, for a total of sixteen additional sessions. Thus, it is possible for a student to triple her simulation exposure through extracurricular sessions.

Unlike the majority of my classmates, I did not participate in the extracurricular simulation sessions. At the time, I did not know that much about simulation and felt that my time could be better spent studying for upcoming tests. Looking back now, having completed my first year of clinical medicine, I very much regret that decision.

When I think back to the simulation experiences I did have, they are overwhelmingly positive. The opportunity to leave textbooks and lectures behind and feel like I was caring for a patient was exhilarating. It was a reminder of *why* I had actually gone to medical school. The fact that the "patient" was a simulation mannequin was irrelevant; I always treated him or her like a human being.

I found that medical simulation clarified for me whether I truly understood and could apply a concept in medicine (ie it helped with both knowledge acquisition and application). It was one thing to be able to draw the graph of cardiac pump function—it was quite another to do a physical exam on a mannequin and determine where on that graph the patient fell and how that determined the proper treatment to administer. According to Dr. Jim Gordon, the Director of the Gilbert Program in Medical Simulation at HMS, the goals of preclinical education for students are to "remember, contextualize, and understand" (J Gordon, personal communication, Nov 5, 2015). Medical simulation helps with the latter two goals by integrating basic and clinical sciences to help students understand and apply the material they are learning in lecture. For more advanced trainees, such as clinical students or residents, simulation may be better used to focus on skills such as teamwork, managing clinical consequences, or performing procedures.

Although attaining clinical competence may not have been a goal of medical simulation for preclinical students, many of my classmates and I felt that simulation helped prepare us for the transition between preclinical and clinical medicine. According to my classmate, Rachel S:

> *In the first two years [of medical school], I struggled with the differential diagnosis of a problem, but simulation forced me to think about what I was actually going to do during third year… Third year was better because I knew what a differential was, had a better idea of what questions to ask the patient, and knew how to navigate a [clinical] situation.* (Rachel S, personal communication, Oct 20, 2015)

Many of my classmates (although not all) reiterated how much more prepared they felt for their clinical years of medical school because of their simulation experiences. It also provided a rare opportunity to learn how to manage acute situations, such as a patient coming in with heat stroke or unresponsive and requiring CPR. Much of our education focused on treating chronic conditions like diabetes or hypertension, which are rarely acutely fatal. It was very different to face a scenario that could be life-or-death and know that we did not have the luxury of time when discussing management options. Although possible to talk through such an acute scenario in class, simulation "allows trainees to assume cognitive responsibility without just discussing," which is a much more realistic experience (J Gordon, personal communication, Nov 5, 2015).

Simulation helps students learn more than just clinical medicine. Several of the classmates I interviewed highlighted the ability of simulation to help learn how to interact with patients who may not always be cooperative. According to my classmate, John Z, "Simulation was not just about the clinical factors but also about the patients themselves. We had comatose patients and argumentative patients. It was really good practice for the clinical years" (Z. Oct 15, 2015.)

Much of our early clinical education focuses on how to take an accurate history from a patient. However, these patients are essentially always cooperative, as they volunteer to talk with students. They tend to talk freely about their life, including topics like their drug use and sexual encounters. When I transitioned to the wards and had to take care of patients, I was unprepared for how often patients did not want to talk to me at all ("I already told the nurse what happened"), were dishonest (a urine toxicology panel disputing what they had told me), or were discourteous toward me (dismissing me because I was a student or a woman). As John described, the opportunity to practice caring for uncooperative patients is extremely valuable as a preclinical student.

Finally, nearly all of my classmates discussed how grateful they were for the chance to practice working in teams during extracurricular simulation. Preclinical education tends to be individual, but simulation exercises involved students working in groups. As Rachel said, simulation was “the first time I had to work with other people. It exposed me to the complexities of personal dynamics and social dynamics and understanding how power played out”(S. Oct 20, 2015.). Another classmate, Daniel R, changed his outlook on teamwork because of his simulation experiences.

> *I was always the person who took charge of teams, but ultimately I realized that I’m more helpful when I’m holding back. I am very confident when I speak and narrow down a diagnosis quickly, but that doesn’t work as well when there is a differential diagnosis 15 items long.* (R. Oct 18, 2015.)

Indeed, Rachel and Daniel’s experiences mirror mine quite well. In my simulation sessions, I found that whether the team worked well together determined how good the patient care was. Early in medical school, teams rarely worked well together because everyone wanted to do everything—we were all so excited to be in a simulation session. As we became more confident in ourselves and each other, it was much easier to assign roles (a team leader, a student to gather the history, a student to do the physical exam, etc.) and stick to them. Clearly defined roles are critical in clinical medicine. Once again, simulation really did help prepare preclinical students for the clinical wards.

All of the students I spoke to felt very positively about their simulation experiences. Their points about simulation’s ability to practice clinical skills, learn how to interact with a variety of patients, and practice teamwork before hitting the wards aligns well with claims made by advocates of medical simulation technology (perhaps even more strongly than the published literature does). Although my classmates and I cannot speak to how simulation may improve the outcomes of our future patients, we can certainly speak to simulation as an exciting and engaging addition to traditional medical school.

In fact, one of the most common critiques was that HMS simply does not incorporate enough simulation into its curriculum when it is such a positive learning experience. According to my classmate, Helen:

> *I wish medical simulation were more frequent and more integrated. The learning was so good compared to most of what we learned in lecture. You were forced to apply your knowledge right away. Within an hour session, you were thinking about an entire pathophysiological process from start to finish. It forced you to take your knowledge and learn it in a way that you needed to know it for clinical medicine.* (Helen D'Couto, personal communication, Oct 18, 2015)

Helen's point fits in well with the transformative potential of SBME. As I discussed earlier, simulation is often not utilized in a transformative manner because of its superficial integration into medical school curricula. For students to experience lasting benefits from SBME, repetitive practice is required. Such repetition is dramatically limited by the infrequent utilization of simulation sessions in medical school.

Overall Assessment of the Technology

This paper set out to examine whether medical simulation technology is capable of merging knowledge acquisition with application by providing simulated patient encounters, particularly for preclinical medical students before they transition to hospital-based settings. This paper further considered whether or not medical simulation technology is transformative or conventional; in other words, whether it is used to “do better things” or “do things better.”

In this concluding section of the paper, I will review the strengths and limits of medical simulation technology, the barriers to widespread adoption (which limit its transformative use), and where the technology is most likely to go in the future.

Strengths and Limits of Medical Simulation Technology

As discussed in this paper, there are many strengths of SBME. SBME gives students an opportunity to integrate basic science and pathophysiological mechanisms of disease with clinical science (thereby promoting knowledge acquisition and application), become familiar with the clinical training environment—including how to interact with patients appropriately and appreciate the time constraints of clinical practice, and provides a safe environment for training that does not expose students or patients to risks. There is strong empirical evidence that skills learned through SBME transfer to real-world scenarios and that simulation-based teaching improves patient outcomes—the ultimate goal of any medical education intervention. Additionally, most students find medical simulation and engaging method of learning and dramatically prefer it to traditional lecture learning.

While most of the evidence is very positive about medical simulation, there are some limits associated with it. In particular, there are concerns that SBME may lead to overconfidence in learners, a trait that particularly problematic within the field of medicine as it may contribute to poor patient outcomes. Additionally, advanced simulation technologies such as computer patients and virtual reality trainers are extremely expensive. Finally, there is variable infrastructure supporting the use of medical simulation across institutions. (Luckily, it is becoming more common for physicians to pursue simulation fellowships, which will increase the number of knowledgeable simulation instructors.)

Barriers to Widespread Adoption

There are two major barriers to widespread adoption of SBME in medical schools and physician-training programs across the country. The first is the prohibitive cost of high-fidelity simulators (HFS) including mannequins and virtual reality trainers. The second is a fundamental disagreement by medical educators over the place of medical simulation in education.

The cost of a top-of-the-line mannequin is on the order of $75,000 (Laerdal 2014). While this many not represent a huge cost to many medical schools, one mannequin is not enough to provide a consistent education to class sizes on the order of hundreds of students. When a school or institution considers buying multiple mannequins, it can often become prohibitively expensive. Ultimately, this limits the transformative use of medical simulation technology. For example, at Harvard Medical School, there are only four mannequins for a class of 200 students (J Gordon, personal communication, Nov 5, 2015). Even if simulation sessions are staggered so that only half the class is doing a simulation at a time, that still leaves 25 students per mannequin. In general, no more than five to six students should be in a single simulation session to maximize learning (otherwise some students are not actively involved in the hands-on learning). It is easy to see how medical simulation cost limits its transformative use.

However, as with most technologies over time, it is very likely that over time, high-fidelity simulation will become cheaper and more affordable. Additionally, since no study has definitively shown that HFS is superior to LFS, institutions could also consider purchasing lower fidelity simulators, which will decrease costs. This might be particularly reasonable for institutions like medical schools, where students are not as clinically advanced and therefore less likely to require the high fidelity aspects of simulation, as compared to resident or attending physicians at hospitals.

The second major barrier to widespread adoption of simulation-based medical education is a disagreement among medical educators over whether medical simulation promotes critical thinking or recognize patterns. Those who think the former push for increased use of medical simulation in medical education; those who think the latter (who often hold positions responsible for these decisions) are hesitant to incorporate fully medical simulation into medical school curricula.

According to Dr. Gordon, many medical educators think that medical simulation is effective only to teach memorizable skills, such as CPR. While it is true that many students *do* learn CPR skills on basic anatomical simulation models, to argue this is the extent of medical simulation ignores 45 years of technological improvement. From my own experiences, a simulation session would never start with the basics of CPR and end with students taking turns on a mannequin.

A much more likely scenario is a mannequin complaining of chest pain, students interviewing the patient and performing a physical exam, creating a differential diagnosis of chest pain, and then proceeding with clinical management (such as administering different medications). It is very possible that during this session, the patient becomes unresponsive, at which point students would then need to start CPR themselves. This simulation session exactly mirrors the type of critical thinking that occurs in a case-based tutorial. The only difference is that students do not simply say what they would do ("I would listen to the heart", "I would start CPR")—they actually do it themselves. In fact, this is where simulation shines—it provides a place for critical thinking and enables students to practice hands-on skills.

It is unfortunate that some medical educators are hesitant to integrate medical simulation into curricula over a misunderstanding of what skills simulation promotes. Hopefully, as more empirical and qualitative evidence builds in support of simulation, there will be greater investment in advancing SBME.

Likely Impact and Evolutionary Path

Medical simulation technology has come a long way since Resusci Anne was first introduced in the 1960s. Since the late 1990s and early 2000s in particular, advancements in medical simulation technology enabled the creation of realistic and high quality virtual reality-based laparoscopic surgical simulators and physiologically responsive mannequins. Every year, the graphics in VR trainers improve and mannequins are capable of exhibiting more realistic behavior, such as sweating or tearing.

Ultimately, this incremental progress in medical simulation is likely to continue every year. Mannequin faces will become more expressive, trainees will be able to practice new types of procedures on mannequins, and improved software will allow instructors to spend less time running the minutiae of the mannequin and more time observing individual actions and team progress. Although mannequin technology will continue to improve, the foundation of the technology is already well established and adapted to help medical trainees learn what is required of them clinically.

In contrast to the incremental improvement that is likely in mannequin technology, there is a revolution awaiting virtual reality-based surgical trainers. A major complaint of current virtual reality trainers is that they lack realistic haptic feedback, which is essential for surgeons who need to be able to differentiate between cutting through skin, fat, muscle, or blood vessels. Some companies try to add a sense of touch to their trainers; however, the technology remains limited (McGaghie et al. 2010). There does appear to be promise on the horizon—earlier this year, engineers at Harvard developed a prototype for a "sensing and force-feedback exoskeleton (SAFE) robotic glove" that provides haptic feedback to each individual finger (Ben-Tzvi and Ma 2015). Such a glove could transform virtual reality trainers if it could simulate haptic feedback from different types of tissue.

Medical simulation will evolve in ways beyond technological improvement. In particular, medical simulation is likely to feature prominently in medical licensure decisions, as flight simulators have done for commercial pilot licensure. Edwin Link created the first flight simulator in 1928, interested in providing a safe and cheap method for learning to fly; after several fatal flying accidents in the early 1930s, the US Army bought several Link trainers to improve pilot skills (Rosen 2008). After a similar series of accidents in the civil aviation industry, in 1955 the Federal Aviation Administration (FAA) required simulation recertification to for pilots to maintain commercial licenses (Rosen 2008).

Initially, airline pilots were reluctant to submit to simulation recertification; today, it is an accepted requirement of the job. Dr. Gordon believes medical simulation is likely to go the same route over the next several decades. Advanced physicians and likely to fight simulation certification because their livelihoods are potentially at stake and due to a frequent belief that simulation cannot adequately measure or assess the complex skills of a physician. Therefore, the push toward competency-based training and practice is most likely to start on the other end of the spectrum, with medical schools requiring students to pass basic simulation scenarios before graduating (J Gordon, personal communication, Nov 5, 2015). One potential benefit of implementing simulation certification for medical students is that simulation is much more likely to be incorporated early and meaningfully into their education, which has great implication for the transformative use of simulation technology.

Over time, similar competency requirements will be incorporated for medical residents and fellows. Because of the distrust established doctors have for simulation recertification, Dr. Gordon thinks that the government will impose such requirements for attending physicians, as was the case in the aviation industry. There is simply too much at stake for patients when physicians do not maintain their skills appropriately.

Ultimately, this will not be a quick process. In fact, I will likely be retired before I myself must undergo simulation recertification. However, I laud the goals of ensuring that medical students and physicians be competent, and I believe that medical simulation offers the possibility to do just this.

Figures

Figure 1 | Asmund Laerdal with his creation, Resusci Anne, 1960s. Courtesy Wikipedia.

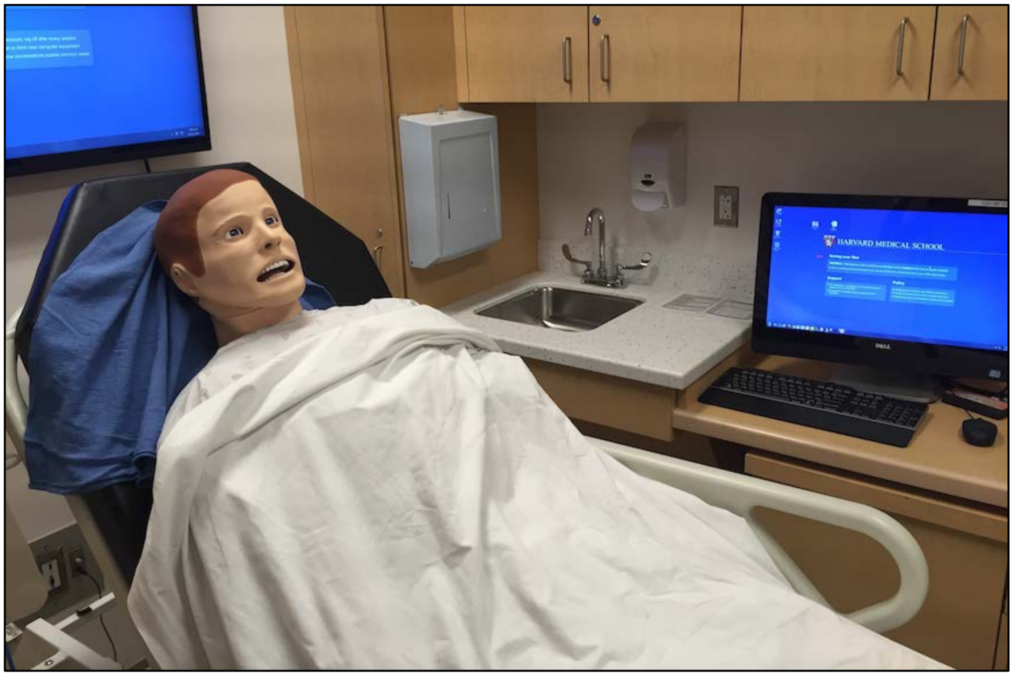

Figure 2 | A simulation mannequin lies on a gurney, with monitors to display vital signs nearby in the Clinical Skills Center at Harvard Medical School. Courtesy the author.

Figure 3 | One of the simulation rooms in the Clinical Skills Center at Harvard Medical School. Simulation instructors sit behind a screen and manage the session using computer software that controls the mannequin and a live video feed so they can monitor students' actions during the session. Courtesy the author.

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