Original Communications

Cost: The missing outcome in simulation-based medical education research: A systematic review

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Background. *The costs involved with technology-enhanced simulation remain unknown. Appraising the value of simulation-based medical education (SBME) requires complete accounting and reporting of cost. We sought to summarize the quantity and quality of studies that contain an economic analysis of SBME for the training of health professions learners.*
Methods. *We performed a systematic search of MEDLINE, EMBASE, CINAHL, ERIC, PsychINFO, Scopus, key journals, and previous review bibliographies through May 2011. Articles reporting original research in any language evaluating the cost of simulation, in comparison with nonsimulation instruction or another simulation intervention, for training practicing and student physicians, nurses, and other health professionals were selected. Reviewers working in duplicate evaluated study quality and abstracted information on learners, instructional design, cost elements, and outcomes.*
Results. *From a pool of 10,903 articles we identified 967 comparative studies. Of these, 59 studies (6.1%) reported any cost elements and 15 (1.6%) provided information on cost compared with another instructional approach. We identified 11 cost components reported, most often the cost of the simulator (*n *= 42 studies; 71%) and training materials (*n *= 21; 36%). Ten potential cost components were never reported. The median number of cost components reported per study was 2 (range, 1–9). Only 12 studies (20%) reported cost in the Results section; most reported it in the Discussion (*n *= 34; 58%).*
Conclusion. *Cost reporting in SBME research is infrequent and incomplete. We propose a comprehensive model for accounting and reporting costs in SBME. (Surgery 2013;153:160-76.)*

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THE WIDESPREAD ADOPTION OF SIMULATION-BASED MEDICAL EDUCATION (SBME) has been fueled, at least in part, by an increase in public awareness and concern for patient safety. The time-honored approach of training health professionals at the patient's bedside may not always be ideal. In some situations, this practice not only puts patients at risk of harm but introduces inefficiencies to the process of patient care.[1] Although SBME can be effective at training health professionals without putting patients at risk,[2] it comes at a price. In fact, the high costs of many simulators has been a key criticism of technology-enhanced simulation.[3]

It is generally believed that investing in medical education will benefit society at large by improving the delivery of healthcare. However, as training expenditures rise with an increased emphasis on technology-based education, we must carefully evaluate the costs of SBME against its outcomes to know how to best allocate resources.[4,5] Published evidence clearly establishes the effectiveness of SBME[2]; however, the evidence on the costs of simulation in

Supported by intramural funds, including an award from the Division of General Internal Medicine, Mayo Clinic.

Accepted for publication June 8, 2012.

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0039-6060/$ - see front matter

http://dx.doi.org/10.1016/j.surg.2012.06.025

medical education has not been systematically investigated. We sought to identify the quantity and quality of cost analysis studies in SBME, examine the types of costs involved, and provide a common framework that will aid in a better understanding and reporting of the financial implications of SBME. We accomplished this through a systematic review.

METHODS

This review was planned, conducted, and reported in adherence to PRISMA standards of quality for reporting systematic reviews.[6] Our methods have been described in detail previously[2]; we focus this description on methods unique to the present study.

Questions. We sought to answer the following questions: (1) What is the frequency and quality of cost-reporting in evaluations of technology-enhanced simulation for the training of health professionals, and (2) What cost components affect the cost of SBME?

Study eligibility. We define technology-enhanced simulation as an educational tool or device with which the learner physically interacts to mimic an aspect of clinical care for the purpose of teaching or assessment.[2]

In the present review, we included studies published in any language that reported the costs of technology-enhanced simulation used to teach health professions learners at any stage in training or practice, and made comparison with another instructional modality. Studies that described costs in general (non-numerical) or rhetorical terms were excluded. We categorized cost-reporting studies as cost-comparative if cost components were reported for the comparison intervention.

Study identification. An experienced research librarian developed a strategy to search MEDLINE, EMBASE, CINAHL, PsychINFO, Scopus, ERIC, and Web of Science. This search had no beginning date cutoff and was updated on May 11, 2011. We added to the screening pool all articles published in *Simulation in Healthcare* and *Clinical Simulation in Nursing* since their inception, all articles cited in several published reviews, and articles identified from the reference lists of 190 included articles. The full identification strategy has been reported previously.[2]

Study selection. Working independently and in duplicate, we screened all titles and abstracts for inclusion. In the event of disagreement or insufficient information in the abstract, we reviewed the full text of potential articles independently and in duplicate, and resolved conflicts by consensus. Chance-adjusted interrater agreement for study inclusion, determined using intraclass correlation coefficient, was 0.69.

Data extraction. We abstracted data independently and in duplicate, resolving conflicts by consensus. Although cost-effectiveness research is well-established in clinical research, we found no published frameworks for systematically and comprehensively identifying and accounting costs in medical education. Thus, we searched the broader field of education and identified Levin's framework for educational cost-effectiveness.[7] This framework identifies 5 broad categories for resources or "ingredients" that contribute to the cost of an educational intervention, namely (a) personnel costs, (b) facility costs, (c) equipment and materials costs, (d) other program inputs, and (e) required client inputs. Using Levin's classifications as a framework, we inductively identified potential cost ingredients specific to SBME by iteratively reviewing the included studies for actual or suggested cost components. Using this model, we then abstracted and classified all reported actual costs for each SBME intervention and each comparison. We recorded the location in the manuscript (Introduction, Methods, Results, or Discussion) in which the most detailed cost data were reported.

We graded the educational quality of each report with the Medical Education Research Study Quality Instrument (MERSQI).[8] Using methods reported previously,[2] we abstracted information and calculated the standardized mean difference (Hedges' g effect size) separately for satisfaction, knowledge, skills (subclassified as time, process, and product measures), behaviors with patients (time and process), and patient effects. We also determined the country of origin, year of publication, training setting, and trainee discipline.

Statistical analysis. We used JMP v9.0.1 (SAS Institute, Cary, NC) for all analyses. Comparisons between cost-comparative and non–cost-comparative studies were performed with Wilcoxon rank-sum test or the chi-square test as appropriate. Significance was defined by a 2-sided alpha of .05. Determinations of clinical significance emphasized Cohen's effect size classifications (<0.2, negligible; 0.2–0.49, small; 0.5–0.8, moderate).[9]

RESULTS

Trial flow. We identified 10,903 potentially relevant articles (Figure). From these, we identified 967 comparative studies of simulation training, of which 59 studies (6.1%) quantified costs involved with simulation training and 15 (1.6%) reported a cost comparison with another instructional modality. These 15 studies, enrolling 1,154 trainees, constitute the main focus of this study, though all 59 cost-reporting studies were used to determine

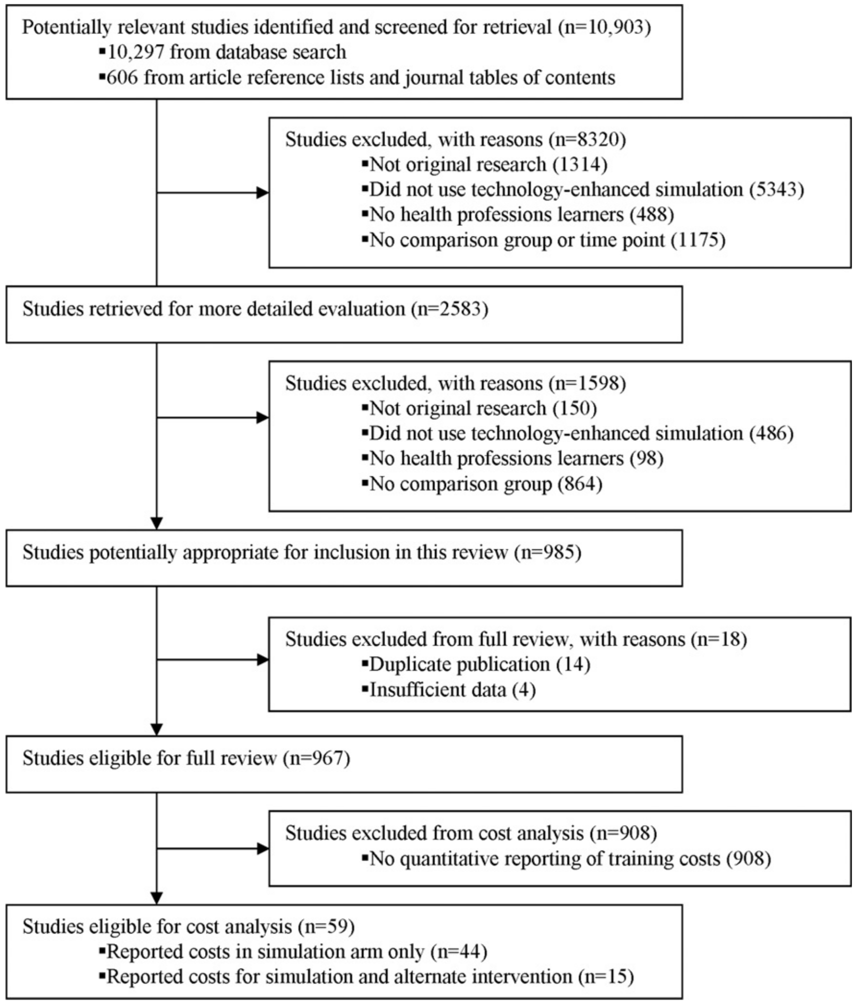

Figure. Flow diagram.

the cost-components. Table I summarizes key features of the 15 cost-comparative studies, and the Appendix contains details of all 59 studies.

Cost components. Overall, we identified 21 cost-components relevant to simulation-based education (Table II). From the 59 cost-reporting studies, we found 11 cost components or "ingredients" reported quantitatively. Drawing upon these sources along with previous work in the field,[3,7,10-13] we identified 10 additional important cost components relevant to SBME that were suggested or implied, but for which quantitative data were not reported.

The most frequently reported cost component category was that of equipment and materials, with the simulator (reported in 42 studies [71%]), training materials (n = 21 [36%]), and simulator maintenance (n = 5 [8%]) being the most frequently reported cost components. We found no cost component corresponding to Levin's other program input's category, such as communication fees (Internet, phone, etc), and other information technology infrastructure needed to support the educational program. We also found gaps in reporting of other important components such as volunteer time, donated equipment, shared costs, furnishing, and other infrastructure costs such as space requirements.

The median number of cost components reported per study was 2 (range, 1–9); 28 studies (47%) reported only 1 cost component. Cost-comparative studies reported significantly more components than non–cost-comparative studies (mean [SD], 3.7 [2.7] vs 1.9 [1.2]; P = .01).

Among the 59 cost-reporting studies, only 12 (20%) reported costs in the Results section; most (n = 34 [58%]) reported costs in the Discussion, 6 (10%) in the Methods, and 4 (7%) in the Introduction. Cost-comparative studies reported the cost component(s) in the Results section of the

Table I. Description of cost-comparative studies

Study	Learner type	No. learners	Specialty	Clinical topic	Region	Group allocation	MERSQI
Petscavage (2011)[15]	PG	44	Radiology	Contrast allergy	USA	RCT	8.5
Delasobera (2010)[17]	EMT	117	EM	ACLS	Asia	Non-RCT	13.5
Stefanidis (2010)[26]	MS	20	Surgery	Laparoscopic skills	USA	RCT	14.5
de Giovanni (2009)[16]	MS	37	IM	Heart sounds	Europe	RCT	
McDougall (2009)[23]	MS	20	Urology	Laparoscopic skills	USA	RCT	15.5
Rosenthal (2009)[25]	MS	20	Surgery	Laparoscopic skills	USA	Non-RCT	11.5
Chandra (2008)[22]	RT	30	Anesthesia	Intubation	Canada	RCT	16
Cho (2008)[24]	PG, MD, RN, EMT	49	EM	Cricothyroidotomy	Asia	RCT	9
de Vries (2008)[38]	RN	30	EM	AED use	Europe	RCT	10.5
Iglesias-Vazquez (2007)[21]	MD, RN	250	EM	ACLS	Europe	RCT	12
Immenroth (2007)[39]	MD	106	Surgery	Laparoscopic skills	Europe	RCT	13.5
Lentz (2005)[40]	PG	41	OB/GYN	Open Surgical skills	USA	Non-RCT	14.5
Grober (2004)[20]	PG	50	Surgery	Microsurgical skills	Canada	RCT	13.5
Matsumoto (2002)[19]	MS	40	Urology	Endoscopic skills	Canada	RCT	14.5
Limpaphayom (1997)[18]	MW	300	OB/GYN	IUD	Asia	Non-RCT	14

ACLS, Advanced cardiac life support skills; *AED*, automated external defibrillator; *EM*, emergency medicine; *EMT*, emergency medical technician/paramedic/first responder or EMT student; *IM*, internal medicine; *IUD*, intrauterine device insertion; *MD*, practicing physician; *MERSQI*, Medical Education Research Study Quality Instrument (maximum score 18); *MS*, medical student; *MW*, midwife; *OB/GYN*, obstetrics and gynecology; *PG*, postgraduate physician trainee; *RCT*, randomized controlled trial; *RN*, nurse or nursing student.

manuscript more often than non–cost-comparative studies ($n = 6/15$ [40%] vs $n = 4/44$ [9%]; $P = .01$), whereas non–cost-comparative studies reported cost component(s) in the Discussion ($n = 28/44$ [64%]) more often than cost-comparative studies ($n = 6/15$ [40%]; $P = .01$). Seven studies reported the total cost of the training intervention without mentioning the cost of any individual cost component. Of the 21 studies that reported the cost of training materials, 11 provided an itemized list specifying the description and cost of each item, whereas the other 10 reported only the total materials cost without a specific breakdown of item costs. Fifteen studies (25%) summed individual cost components and divided the total cost by the number of learners to report the cost per learner.

One study reported cost outcomes by reporting the costs of the training activity in comparison with the estimated cost of patient complications that would be expected in the absence of training.[14] Although the training costs were high ($111,916), the monetary benefit from reduced costs of care ($823,164) suggested a large net savings.

Characteristics of cost-comparative studies. Of the 15 cost-comparative studies, 4 studies compared the costs of simulation with another instructional modality, and 11 with another technology-enhanced simulation intervention (Table III). Most cost-comparative studies ($n = 11$ [73%]) were published in or after 2007. The most frequent region of origin was the United States ($n = 5$ [33%]), followed by Europe ($n = 4$ [27%]), then Canada and Asia ($n = 3$ each). All studies were performed in a simulated setting. The 15 cost-comparative studies reported 41 cost components, with the cost of the training materials ($n = 11$ [27%]), the simulator ($n = 9$ [22%]), staff time ($n = 5$ [12%]), and staff fee ($n = 5$ [12%]) being the most frequently compared cost components.

Quality of cost-comparative studies. The number of participants providing outcomes ranged from 20 to 300 with a median of 41 (interquartile range, 30–106). Groups were randomly assigned in 11 (73%) studies. The mean (SD) MERSQI score was 12.9 (2.3) of a maximum of 18.

Comparative costs. Four studies compared the costs of technology-enhanced simulation with nonsimulation training. Two studies showed that simulation costs more and is educationally more effective,[15,16] one showed it is more costly and similarly effective,[17] and 1 study showed that it is less costly and more effective per unit of time.[18] Hence, it seems that the relationship between the costs of simulation and its benefits depends on the specific implementation under study.

Eleven studies compared ≥2 active simulation interventions. The most common theme was comparisons between high-fidelity and low-fidelity

Table II. Essential cost ingredients in simulation-based education, and frequency of reporting

Levin's cost categories	*Cost ingredients*	*Description/examples*	*Studies* (n = 59), n (%)
Equipment and materials	Equipment purchase	Market price of simulator, computer, smartphone, projector, etc	42 (71)
	Training materials	Costs of materials involved in training either reported in an itemized or lumped (all together) fashion	21 (36)
	Equipment maintenance	Annual fee, upgrades, tech support	5 (8)
	Equipment depreciation	Percentage of the annual price drop in the value of the equipment	3 (5)
	Durability of materials	Length of time or number of attempts before materials need to be replaced	3 (5)
	Donations*	Donated equipment	0
	Shared costs	Use of equipment by different learner populations	0
	Furnishing	Furniture or appliances needed to support the equipment	0
Personnel cost	Staff fee	Staff salary per hr or day of instruction	6 (10)
	Number of staff	Quantity of personnel needed to run and prepare the course	6 (10)
	Staff time	Time needed to teach and/or prepare the course	6 (10)
	Volunteer time*	Time that teachers and other staff may be expected to contribute beyond their paid workday	0
	Administrative staff	Staff requirements to run the administrative components of the program	0
	Staff training	Cost of training for instructors	0
Facility costs	Facility rental fee	For rented facilities: Fee per hr or day of use	5 (8)
	Facility cost	For facilities that have been constructed or purchased: the depreciation of the building and interest on the remaining undepreciated original value	0
	Facility maintenance	Building upkeep, lighting, air conditioning, heating, electricity	0
Required client inputs	Learner costs	Expenses incurred by the learner (transportation, meals, course registration, books, etc)	2 (5)
	Opportunity cost	Costs that are incurred from taking time to learn or to teach (ie, lost clinical revenue from staff when taking time to teach)	1 (2)
Other program inputs	Information technology	Camera, video recording and viewing equipment, servers for storage and retrieval of information and video	0
	Communication fees	Telephone and Internet access fees	0

*Donated equipment and volunteer time should be accounted because, although these ingredients did not incur cost in the reported study, they would incur cost in most future implementations.

models in 5 studies.[19-23] Most studies concluded that low-fidelity simulators were similarly effective but less expensive than high-fidelity simulators. One study demonstrated superior efficacy with a high-fidelity model but at a much greater expense.[21] However, higher fidelity did not always cost more. One study compared porcine versus manikin models for cricothyroidotomy training and found the higher fidelity porcine model to be more realistic, preferred by the learner, and less expensive; however, effectiveness (ie, skill or behavior outcomes) was not assessed in this setting.[24] Two studies evaluated the impact of different simulation-based pre-training regimens before the Fundamentals of Laparoscopic Skills course[25,26]; both concluded that pretraining decreases training time and expenses during the course.

Table III. Comparative costs of simulation

Citation	*Cost: intervention #1 or simulation*	*Cost: intervention #2 or non-simulation*	*Outcomes and effect sizes**
TE-SIM vs nonsimulation modality			
Petscavage (2011)[15]	Simulated scenario with high-fidelity simulator: $259 per resident	Lecture: <$5 per resident	Knowledge 1.19 (B) Reaction 1.3 (B)
Delasobera (2010)[17]	High-fidelity simulator: $23,463	#1: Multimedia computer game: $119 #2: Textbook $66	#1. Knowledge -0.21 (D) Skill product 0.15 (B) #2. Knowledge 1.1 (B) Skill product 0.52 (B)
de Giovanni (2009)[16]	High-fidelity simulator Harvey: $75,000	Multimedia CD: $130	Skill product 0.4 (B)
Limpaphayom (1997)[18]	Two-week course (lecture, mannequin, real patients): $910.69 per learner	Six-week course (lecture, real patients): $2,809.44 per learner	Behavior process 2.8 (A) Knowledge 0.47 (A) Skill product 0.26 (A) Reaction 0.78 (A)
TE-SIM vs TE-SIM			
Stefanidis (2010)[26]	Laparoscopic box trainer pre-training + FLS: $159 ± 37 per learner	FLS: $307 ± 89 per learner	Skill process 1.5 (A) Skill time 1.5 (A)
McDougall (2009)[23]	Pelvic Model: $22,960 or $1,290 (with cost-reduction strategies) + instructor salary: $200 per hr	Laparoscopic virtual reality simulator: $89,000 + maintenance: $8,000–$15,000	Skill process 0.09 (A) Skill time 0.08 (A) Reaction 0.31 (A)
Rosenthal (2009)[25]	Laparoscopic box trainer pre-training + FLS: $827 ± 116 per learner	FLS: $1,108 ± 393 per learner	Skill process –0.77 (C) Skill time 1.3 (A)
Chandra (2008)[22]	Fiberoptic intubation high-fidelity simulator: $100,000	Fiberoptic intubation low-fidelity model: $20	Behavior process –0.21 (D) Behavior time –0.45 (D)
Cho (2008)[24]	Cricothyroidotomy animal model: $4	Cricothyroidotomy manikin model: $20	Reaction 1.09 (A)
de Vries (2008)[38]	Self-learning group: €12 per learner	Instructor present group: €59 per learner	Skill process –0.11 (C)
Iglesias-Vazquez (2007)[21]	High-fidelity manikin: €1320 per learner	Low-fidelity manikin: €392 per learner	Skill process 0.39 (B)
Immenroth (2007)[39]	Basic simulation + additional task trainer practice: $360 per task trainer practice session	Basic simulation + mental imagery training: $120 per mental training session	Skill process 0 (D)
Lentz (2005)[40]	Yearlong course of animate simulator training: $12,000 animal laboratory + 57 hrs of faculty time	Yearlong course with inanimate simulator training: $3,000 for supplies	Knowledge 1.44 (B) Skill process 0.29 (B)
Grober (2004)[20,†]	High-fidelity bench model: $55 CDN per trainee	Low-fidelity bench model: $1.5 CDN per trainee	Skill process 0.15 (B) Skill product –0.22 (D) Skill time 0.17 (B)
Matsumoto (2002)[19,†]	High-fidelity bench model: $3,700 CDN	Low-fidelity bench model: $20 CDN	Skill process 0.71 (B) Skill product 0.3 (B) Skill time –0.16 (D)

*Positive effect size favors intervention #1/simulation; <0.2 = negligible; 0.2–0.5 = small; 0.5–0.8 = moderate; and >0.8 = large. Letters in parentheses indicate that Intervention 1 or Simulation is: A = more effective, less expensive; B = more effective, more expensive; C = less effective, less expensive; and D = less effective, more expensive.

†Also had a comparison with nonsimulation instruction (lecture); however, no comparative cost data was provided for the nonsimulation instruction.

€, Euros; $, US dollars; *CDN*, Canadian dollars; *FLS*, Fundamentals of Laparoscopic Skills Program[41]; *TE-SIM*, technology-enhanced simulation.

DISCUSSION

Evidence shows that SBME improves learner outcomes compared with no intervention[2] and other educational activities.[27] However, the cost entailed in achieving these outcomes is less clear. Fewer than 2% of the studies identified in our literature search reported information regarding the comparative costs associated with simulation training and other educational options. Even among these studies, cost accounting generally involved only 1 or 2 components and thus may fail to reflect the complete costs associated with either the simulation or the alternative. Educators, administrators, and funding agencies want to know the cost-effectiveness of SBME. However, we cannot determine cost-effectiveness until we first understand how to clearly account for costs. Unfortunately, despite increased attention in the past 5 years, cost reporting remains incompletely understood and infrequently done. In an effort to generate a comprehensive cost-reporting framework that applies to SBME, we draw on cost-reporting frameworks used in the general education literature and offer potential avenues to adapt these to our purposes.

Cost reporting frameworks. The most commonly used approach to cost reporting in education is the ingredients model proposed by Levin.[10] It comprises 3 steps: First, all resources or ingredients must be identified. Second, monetary values must be placed on each ingredient. Third, the total cost of each alternative is summed and expressed as a cost-per-learner to enable comparison among alternatives. Although less commonly used, resource cost modeling, provides an alternate framework for cost analysis.[12] It differs from the ingredients approach in the initial stages of modeling, in which resource cost modeling provides a more complex division of cost categories.

The adoption of either model provides the researcher with a general framework for determining which ingredients should be considered in the cost analysis. However, neither model dictates how actual monetary values should be assigned to each ingredient. In fact, the assignment of monetary values to ingredients involves a multistep process of estimation, adjustment, and analysis. These steps include (a) valuing ingredients, (b) adjusting for inflation, (c) discounting costs, (d) calculating net present value, (e) conducting a sensitivity analysis, and (f) analyzing the distributional consequences of costs. Although a detailed discussion of these issues is beyond the scope of this review, we have briefly defined these steps in Table IV, and refer interested readers to the work of White et al[12] and Levin and McEwan.[7,28]

Overall, different methods of cost analysis exist, each intended to answer a specific question. The majority of studies in this review frequently focused on the equipment and materials cost, predominantly the price of the simulator, and thus were of the most limited type of cost analysis: Basic cost or cost feasibility analysis. These are useful if an evaluator simply wants to know how much a particular program or intervention will cost and whether it can be implemented within existing budgetary constraints. If, on the other hand, an evaluator wants to be able to reach conclusions not just about cost, but also about the relative effectiveness or utility of a range of programs or interventions, a cost-benefit, cost-effectiveness, or cost-utility analysis is required.[7,10,25] Such studies would provide the evidence needed by educators, researchers, and policymakers to make informed decisions about education expenditures.[8,29]

Limitations and strengths. Systematic reviews are limited by the quantity and quality of published evidence. Because so few studies reported costs, and most of these reports are incomplete, the evidence does not permit meaningful pooling of results across studies. Although the sample of eligible studies was relatively small, their quality as reflected by MERSQI scores was generally higher than studies in previous reviews of medical education research.[2,8,30,31] Because studies without a comparison point are difficult to interpret and apply, we focused on comparative studies of simulation, and therefore cannot comment on the frequency of cost reporting in noncomparative studies.

Strengths of our study include the exhaustive literature search led by an experienced reference librarian; no restriction based on time or language of publication; explicit inclusion criteria encompassing a broad range of learners, outcomes, and study designs; duplicate, independent, and reproducible data abstraction; rigorous coding of methodologic quality; and focused analyses. The inclusion of diverse specialties and training levels increased the number of studies evaluated in the derivation of our model, and enhances the comprehensiveness and generalizability of our findings. The importance of cost-effectiveness in medical education will only increase in coming years. Although our findings emerged from the field of SBME, we believe the message is of relevance to medical education broadly.

Comparisons with previous reviews. Brown et al[32] reviewed the literature on the cost effectiveness of continuing professional development courses in health care and found only 9 studies

Table IV. Overview of steps in assigning monetary value to resources

Step	*Explanation*
Valuing ingredients	The most common way of assigning value to a commodity or resource is using its market price or actual current price. Though straightforward in most circumstances, it may not represent the true value of a resource when the market is not in a state of equilibrium, there are few buyers or sellers in the market, or product demand is likely to change. If such instability exists, the researcher can use a "shadow price" (the current price an informed consumer would be willing to pay after comparison with other similar products) or a hybrid approach. The assignment of monetary values to more subjective items such as volunteer time or facilities costs poses an extra layer of complexity. For example, volunteer time is valued by estimating the hrly salary applicable to the qualifications of individual, and the value of a facility can be calculated by estimating its rental value. When no cost information is available, it may be helpful to break ingredients down into their constituent parts and add the value of those parts to estimate the cost of the whole.
Adjusting for inflation	When evaluating a multiyear project, or comparing projects implemented at different times, ingredient costs must be adjusted for inflation, typically by using a consumer price index (CPI, U.S. Department of Labor).[42]
Discounting costs	Resources used in an intervention today could theoretically be invested elsewhere and earn interest over time. Discounting accounts for the premise that costs occurring in the future are less of a burden than costs occurring in the present.
Calculating net present value	In this step the total present cost is calculated, taking into account inflation and discounting.
Conducting sensitivity analysis	Nearly every cost analysis makes assumptions in the estimation of costs and benefits. Sensitivity analyses explore the effects of such assumptions by varying, for example, the monetary estimates for resources with imprecise values, the inflation rate, or discount rate. A net present value that is robust to such variations can be trusted with confidence.
Analyzing distributional consequences	Costs and outcomes are rarely distributed evenly across groups or individuals (medical students vs residents, small vs large sized program, academic vs community center, Dean's office vs program director). Some bear a greater burden of costs, and some may benefit more. The way outcomes are distributed across different groups of individuals can affect conclusions about the relative cost-effectiveness of alternatives for different populations of individuals. To account for distributional consequences, the net present value estimates are separated (disaggregated) according to a predefined set of stakeholder groups so that each group can understand the individual cost impact.

Adapted from White et al[12] and Levin and McEwan.[7,28]

(unspecified denominator), of poor quality and with limited scope for generalization. A recent book has also lamented the infancy of cost-effectiveness research in medical education.[3] Additionally, Prystowsky et al[4] found that cost was the focus of only 2.3% of 599 articles published between 1996 and 1998 in 3 leading medical education journals. However, the paucity and poor quality of cost-effectiveness research in education is not limited to medical education. Clune[11] evaluated the methodologic strength and policy usefulness of cost-effectiveness research in the elementary and secondary education literature published between 1991 and 1996. His findings that only 1% of 541 "cost-effectiveness" studies could be considered reliable, with strong design and analysis, suggesting that cost-effectiveness research in education was scarce, of poor quality, and failed to inform the public.

The relative paucity of cost-analysis studies in education and the poor quality of what does exist is puzzling, especially in comparison with the quantity and strength of the cost-effectiveness literature in clinical medicine.[10,33] To explain this phenomenon, Levin[10] turned to the principle of supply and demand. The supply of cost-effectiveness research in education is limited by a lack of educators trained in the methods of cost-effectiveness analysis and by concerns that cost estimates would be superfluous when education research cannot provide unambiguous estimates of effect. However, the lack of demand is believed to be an even more important factor. If policymakers and stakeholders do not require cost-effectiveness research, we should not be surprised to find few studies. In fact, such a lack of interest from policymakers regarding cost-effectiveness research in medical education is exemplified in the comparative-effectiveness research priorities of the Institute of Medicine and the Agency for Health Care Research and Quality, which do not mention of the effect that health professions education on the delivery of healthcare.[34-36]

Implications. Although many authors use the term cost-effectiveness, the vast majority of the reports in this review present incomplete accounting of costs, and none reported a formal cost-effectiveness analysis. However, we applaud those who have made the effort to report costs, and hope that others can build on these efforts to conduct full cost-effectiveness studies. In these times of heightened economic awareness and pressure to demonstrate the value of the investments in medical education, researchers who evaluate the effectiveness of SBME should consider the financial implications of the educational intervention. We suggest that reviewers and journal editors encourage authors to report cost data in manuscripts addressing the effects of SBME.

The cost of simulation typically increases as the fidelity increases, and many assume that higher fidelity simulators will be more effective. However, less can be more. In fact, several of the studies included within this review compared high- versus low-fidelity models, and consistently found that low-fidelity models can be similarly effective and less expensive compared with their high-fidelity counterparts.[3,19,20,24] Additionally, evidence as far back as 25 years suggests that novices seem to benefit more from low fidelity, as opposed to experts who may respond better to greater fidelity.[37] Therefore, we may be able to reduce the costs of simulation by matching the educational intervention to the learner's needs; this requires research to determine where and when to best to situate high- and low-fidelity simulators within a curriculum.

A few points are particularly relevant for cost-accounting in a relatively new and rapidly changing. First, a complete and realistic accounting of costs is essential. Failure to count donated time and equipment underestimates costs, and amortizing fixed costs over a few learners in a research study overestimates the per-person costs compared with implementation on a broader scope. Second, as noted (see also Table IV), estimating the cost of many ingredients, including donated time, building space, and equipment, require approximations and assumptions. Sensitivity analyses in which assumptions and approximations are systematically varied will be particularly important when presenting such results. Third, the price of many ingredients could change substantially over time or by location. For example, a simulator's price might rapidly rise or fall depending on its popularity or the launch of a rival product. Clinical revenues and charges also factor into the opportunity cost of staff time and the benefits of training, and these costs vary over time and from institution to institution. Finally, there may be costs, both economic and nonmonetary, of not engaging in certain educational activities; such would enter into a comprehensive, cost-effectiveness analysis.

Although Levin's proposed categories of cost ingredients are relatively straightforward, no single approach to categorization will be suitable in all cases. Hence, the extent to which the ingredients model provides a useful heuristic for organizing cost information depends a great deal on the research question, resources, and planned analyses.[12] The model we propose couples Levin's ingredients framework with specific cost components identified empirically in this review of SBME. Authors can use this model as a starting point as they plan and report studies that document the costs of simulation in medical education. We acknowledge that accounting the cost of health professions education will be a complex endeavor. These are, as yet, largely untested waters, and many questions regarding the optimal approach remain unanswered. For example, what are the forces that drive the costs of education in one direction or another? As our healthcare system becomes more complex, it will be increasingly important not to only account for all the relevant costs, but also understand and account for their behavior. This review, and the cost ingredients model we derived, represents an important first step toward this goal.

The authors thank Rose Hatala MD, MSc, Jason H. Szostek, MD, and Patricia J. Erwin MLS, for their assistance with data collection.

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Appendix. Full list of all studies reporting cost (n = 59)*

Citation	*Trainee*	*N*	*Geographic origin*	*Comparison*	*RCT*	*MERSQI*	*Cost-comparative*
Holzman GB, et al. Initial pelvic examination instruction: The effectiveness of three contemporary approaches. Am J Obstet Gynecol 1977;129:124–9.	MS	38	US	SS		12.5	
Hegstad LN, et al. A study of the cost-effectiveness of providing psychomotor practice in teaching intravenous infusion techniques. J Nurs Educ 1986;25:10–4.	RN	74	US	NI	RCT	11.5	
Homan CS, et al. Evaluation of an emergency-procedure teaching laboratory for the development of proficiency in tube thoracostomy. Acad Emerg Med 1994;1:382–7.	MS, PG	12	US	NI		11	
Limpaphayom K, et al. The effectiveness of model-based training in accelerating IUD skill acquisition. A study of midwives in Thailand. Br J Fam Plann 1997;23:58–61.	O	300	Asia	MC		14	X
Farnsworth ST, et al. Teaching sedation and analgesia with simulation. J Clin Monit Comput 2000;16:273–85.	RN	20	US	NI		11	
Knudson MM, et al. Training residents using simulation technology: experience with ultrasound for trauma. Journal of Trauma: Injury Infection & Critical Care 2000;48:659–65.	PG	74	US	MC		12	
Scott DJ, et al. Laparoscopic training on bench models: better and more cost effective than operating room experience? J Am Coll Surg 2000;191:272–83.	PG	27	US	NI	RCT	14	
Tsai M-D, et al. Virtual reality orthopedic surgery simulator. Comput Biol Med 2001;31:333–51.	PG, MD	16	Asia	MC		6	
Kothari SN, et al. Training in laparoscopic suturing skills using a new computer-based virtual reality simulator (MIST-VR) provides results comparable to those with an established pelvic trainer system. J Laparoendosc Adv Surg Tech 2002;12:167–73.	MS	29	US	SS	RCT	12.5	
Matsumoto ED, et al. The effect of bench model fidelity on endourological skills: a randomized controlled study. J Urol 2002;167:1243–7.	MS	40	Can	MC, SS	RCT	14.5	X

(*continued*)

Appendix. (*continued*)

Citation	*Trainee*	*N*	*Geographic origin*	*Comparison*	*RCT*	*MERSQI*	*Cost-comparative*
Gerson LB, et al. A prospective randomized trial comparing a virtual reality simulator to bedside teaching for training in sigmoidoscopy. Endoscopy 2003;35:569–75.	PG	16	US	MC		13.5	
Blum MG, et al. Bronchoscopy simulator effectively prepares junior residents to competently perform basic clinical bronchoscopy. Ann Thorac Surg 2004;78:287–91.	PG	10	US	NI	RCT	13	
Grober ED, et al. The educational impact of bench model fidelity on the acquisition of technical skill: the use of clinically relevant outcome measures. Ann Surg 2004;240:374–81.	PG	50	Can	MC, SS	RCT	13.5	X
Sedlack RE, et al. Computer simulator training enhances the competency of gastroenterology fellows at colonoscopy: results of a pilot study. Am J Gastroenterol 2004;99:33–7.	PG	8	US	NI	RCT	13	
Hall RE, et al. Human patient simulation is effective for teaching paramedic students endotracheal intubation. Acad Emerg Med 2005;12:850–5.	EMT	36	Can	MC	RCT	12.5	
Korndorffer JR, Jr., et al. Development and transferability of a cost-effective laparoscopic camera navigation simulator. Surg Endosc 2005;19:161–7.	MS	20	US	NI	RCT	13.5	
Lentz GM, et al. A six-year study of surgical teaching and skills evaluation for obstetric/gynecologic residents in porcine and inanimate surgical models. Am J Obstet Gynecol 2005;193:2056–61.	PG	41	US	SS		14.5	X
Matthes K, et al. Efficacy and costs of a one-day hands-on EASIE endoscopy simulator train-the-trainer workshop. Gastrointest Endosc 2005;62:921–7.	PG	8	US	NI		12	
Ault MJ, et al. The use of tissue models for vascular access training: phase I of the procedural patient safety initiative. J Gen Intern Med 2006;21:514–7.	PG, MD	126	US	NI		9	
Levine RL, et al. The use of lightly embalmed (fresh tissue) cadavers for resident laparoscopic training. J Minim Invasive Gynecol 2006;13:451–6.	PG	29	US	NI		9	

(*continued*)

Appendix. (*continued*)

Citation	Trainee	N	Geographic origin	Comparison	RCT	MERSQI	Cost-comparative
Cherry RA, et al. The effectiveness of a human patient simulator in the ATLS shock skills station. J Surg Res 2007;139:229–35.	PG	44	US	SS	RCT	13.5	
Iglesias-Vazquez JA, et al. Cost-efficiency assessment of Advanced Life Support (ALS) courses based on the comparison of advanced simulators with conventional manikins. BMC Emergency Medicine. 2007;7:18.	MD, RN	250	Eur	SS	RCT	12	X
Immenroth M, et al. Mental training in surgical education: a randomized controlled trial. Ann Surg 2007;245:385–91.	MD	106	Eur	SS	RCT	13.5	X
Scott DJ, et al. A cost-effective proficiency-based knot-tying and suturing curriculum for residency programs. J Surg Res 2007;141:7–15.	PG	4	US	NI		10	
Chandra DB, et al. Fiberoptic oral intubation: the effect of model fidelity on training for transfer to patient care. Anesthesiology 2008;109:1007–13.	O	30	Can	SS	RCT	16	X
Cho J, et al. Comparison of manikin versus porcine models in cricothyrotomy procedure training. Emerg Med J 2008;25:732–4.	PG, MD, RN, EMT	49	Asia	SS	RCT	9	X
Friedman Z, et al. Teaching lifesaving procedures: the impact of model fidelity on acquisition and transfer of cricothyrotomy skills to performance on cadavers. Anesth Analg 2008;107:1663–9.	PG	22	Can	SS	RCT	12.5	
Scott DJ, et al. Certification pass rate of 100% for fundamentals of laparoscopic surgery skills after proficiency-based training. Surg Endosc 2008;22:1887–93.	MS	21	US	NI		12.5	
Summerhill EM, et al. A simulation-based biodefense and disaster preparedness curriculum for internal medicine residents. Med Teach 2008;30(6):e145–51.	PG	60	US	NI		11.5	
Tsai S-L, et al. The use of virtual reality computer simulation in learning Port-A cath injection. Adv Health Sci Educ Theory Pract 2008;13:71–87.	RN	82	Asia	MC	RCT	14.5	
de Vries W, et al. Self-training in the use of automated external defibrillators: the same results for less money. Resuscitation 2008;76:76–82.	RN	30	Eur	SS	RCT	10.5	X

(*continued*)

Appendix. (*continued*)

Citation	*Trainee*	*N*	*Geographic origin*	*Comparison*	*RCT*	*MERSQI*	*Cost-comparative*
Bjorshol CA, et al. Hospital employees improve basic life support skills and confidence with a personal resuscitation manikin and a 24-min video instruction. Resuscitation 2009;80:898–902.	O	1,333	Eur	NI		11	
Dayal AK, et al. Simulation training improves medical students' learning experiences when performing real vaginal deliveries. Simul Healthc 2009;4:155–9.	MS	33	US	NI	RCT	13.5	
Dorman K, et al. Addressing the severe shortage of health care providers in Ethiopia: bench model teaching of technical skills. Med Educ 2009;43:621–7.	PG	19	Afr	NI		11	
Kardong-Edgren S, et al. VitalSim versus SimMan: a comparison of BSN student test scores, knowledge retention, and satisfaction. Clinical Simulation in Nursing 2009;5:e105–11.	RN	118	US	NI, SS	RCT	14.5	
McDougall EM, et al. Preliminary study of virtual reality and model simulation for learning laparoscopic suturing skills. J Urol 2009;182:1018–25.	MS	20	US	SS	RCT	15.5	X
Narra P, et al. Videoscopic phantom-based angiographic simulation: effect of brief angiographic simulator practice on vessel cannulation times. J Vasc Interv Radiol 2009;20:1215–23.	MS, PG	40	US	MC	RCT	12.5	
Okrainec A, et al. Surgical simulation in Africa: the feasibility and impact of a 3-day Fundamentals of Laparoscopic Surgery course. Surg Endosc 2009;23:2493–8.	PG, MD	20	Afr	NI		13.5	
Panait L, et al. The role of haptic feedback in laparoscopic simulation training. J Surg Res 2009;156:312–6.	MS	10	US	SS		11.5	
Rosenthal ME, et al. Pretraining on Southwestern stations decreases training time and cost for proficiency-based fundamentals of laparoscopic surgery training. J Am Coll Surg 2009;209:626–31.	MS	20	US	SS		11.5	X
Sotto JAR, et al. Exporting simulation technology to the Philippines: a comparative study of traditional versus simulation methods for teaching intravenous cannulation. Stud Health Technol Inform 2009;142:346–51.	MS	40	Asia	MC	RCT	16.5	

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Appendix. (*continued*)

Citation	*Trainee*	*N*	*Geographic origin*	*Comparison*	*RCT*	*MERSQI*	*Cost-comparative*
Walker JB, et al. A novel simulation model for minimally invasive spine surgery. Neurosurgery 2009;65(6 Suppl):188–95.	PG	8	US	NI		8	
de Giovanni D, et al. Relative effectiveness of high- versus low-fidelity simulation in learning heart sounds. Med Educ 2009;43:661–8.	MS	37	UK	MC	RCT	14.5	X
Andreatta PB, et al. Virtual reality triage training provides a viable solution for disaster-preparedness. Acad Emerg Med 2010;17:870–6.	PG	15	US	MC	RCT	12.5	
Cohen ER, et al. Cost savings from reduced catheter-related bloodstream infection after simulation-based education for residents in a medical intensive care unit. Simul Healthc 2010;5:98–102.	PG	0.69	US	NI		13	X
Conroy SM, et al. Competence and retention in performance of the lumbar puncture procedure in a task trainer model. Simul Healthc 2010;5:133–8.	PG	30	US	NI		13	
Delasobera BE, et al. Evaluating the efficacy of simulators and multimedia for refreshing ACLS skills in India. Resuscitation 2010;81:217–23.	EMT	117	Asia	MC		13.5	X
Ford DG, et al. Impact of simulation-based learning on medication error rates in critically ill patients. Intensive Care Med 2010;36:1526–31.	RN	24	US	MC		13	
Hishikawa S, et al. Mannequin simulation improves the confidence of medical students performing tube thoracostomy: a prospective, controlled trial. Am Surg 2010;76:73–8.	MS	30	Asia	NI	RCT	13.5	
Leblanc F, et al. Hand-assisted laparoscopic sigmoid colectomy skills acquisition: augmented reality simulator versus human cadaver training models. J Surg Educ 2010;67:200–4.	MD	34	US	SS		11.5	
Martínez AM, et al. Adaptation to a dynamic visual perspective in laparoscopy through training in the cutting task. Surg Endosc 2010;24:1341–6.	PG	26	US	SS		10.5	

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Appendix. (*continued*)

Citation	*Trainee*	*N*	*Geographic origin*	*Comparison*	*RCT*	*MERSQI*	*Cost-comparative*
Stefanidis D, et al. Initial laparoscopic basic skills training shortens the learning curve of laparoscopic suturing and is cost-effective. J Am Coll Surg 2010;210:436–40.	MS	20	US	SS	RCT	14.5	
Tongprasert F, et al. Training in cordocentesis: the first 50 case experience with and without a cordocentesis training model. Prenat Diagn 2010;30:467–70.	MD	10	Asia	NI		13	
Unalan PC, et al. A basic arthroscopy course based on motor skill training. Knee Surg Sports Traumatol Arthrosc 2010;18:1395–9.	PG, MD	64	Eur	NI		10	
Williams DJ, et al. Validation of a novel fibreoptic intubation trainer. Anaesthesia 2010;65:18–22.	MS, PG, MD	76	UK	NI		11	
Fraser K, et al. Simulation training improves diagnostic performance on a real patient with similar clinical findings. Chest 2011;139:376–81.	MS	86	Can	SS	RCT	11.5	
Kern DH, et al. Simulation-based teaching to improve cardiovascular exam skills performance among third-year medical students. Teach Learn Med 2011;23:15–20.	MS	405	US	NI		10.5	
Parker RA, et al. Pediatric clinical simulation: a pilot project. J Nurs Educ 2011;50:105–11.	RN	41	US	MC	RCT	12.5	
Petscavage JM, et al. Cost analysis and feasibility of high-fidelity simulation based radiology contrast reaction curriculum. Acad Radiol 2011;18:107–12.	PG	44	US	MC	RCT	8.5	

*Articles are sorted in descending order by year and then by first author's last name.
EMT, Emergency medical technician/paramedic/first responder or EMT student; *Can*, Canada; *Eur*, Europe; *MC*, media comparative; *MD*, practicing physician; *MERSQI*, Medical Education Research Study Quality Instrument (maximum score 18); *MS*, medical student; *n*, number of outcome observations (group 1, group 2; usually the number of trainees, but in some cases the number of teams observed or of patient observations); *NI*, nonintervention; *O*, other/mixed; *PG*, postgraduate physician trainee; *RCT*, randomized controlled trial; *RN*, nurse or nursing student; *SS*, technology-enhanced simulation; *UK*, United Kingdom; *US*, United States of America.