Original Article

Estimated Cost Savings from Reducing Errors in the Preparation of Sterile Doses of Medications

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ABSTRACT

Background: Preventing intravenous (IV) preparation errors will improve patient safety and reduce costs by an unknown amount.

Objective: To estimate the financial benefit of robotic preparation of sterile medication doses compared to traditional manual preparation techniques.

Methods: A probability pathway model based on published rates of errors in the preparation of sterile doses of medications was developed. Literature reports of adverse events were used to project the array of medical outcomes that might result from these errors. These parameters were used as inputs to a customized simulation model that generated a distribution of possible outcomes, their probability, and associated costs.

Results: By varying the important parameters across ranges found in published studies, the simulation model produced a range of outcomes for all likely possibilities. Thus it provided a reliable projection of the errors avoided and the cost savings of an automated sterile preparation technology. The average of 1,000 simulations resulted in the prevention of 5,420 medication errors and associated savings of \$288,350 per year. The simulation results can be narrowed to specific scenarios by fixing model parameters that are known and allowing the unknown parameters to range across values found in previously published studies.

Conclusions: The use of a robotic device can reduce health care costs by preventing errors that can cause adverse drug events.

Key Words—drug contamination, medication errors, patient safety

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Adverse events associated with errors in compounding sterile medications have again become an issue of public concern.¹ Pharmacists must renew their vigilance in ensuring the accuracy and sterility of compounded sterile medications if they are to maintain the public trust and avoid onerous regulation. Pharmacists are also focusing more on the clinical use of medications by delegating technical tasks, including drug preparation, to qualified technicians or by using technology.² This transformation of the pharmacy profession will

require a careful transition in critical tasks, such as compounding sterile preparations, for quality to be ensured, if not improved.

This is not the first time that errors associated with compounding sterile preparations have been reported. Previous incidences prompted the US Food and Drug Administration (FDA) to consider regulating compounding as manufacturing. Concerns within the profession of pharmacy about impending regulations prompted the publication of the Draft Guidelines on Quality Assurance for Pharmacy-Prepared Sterile

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Products and the American Society of Health-System Pharmacists (ASHP) Technical Assistance Bulletin on Quality Assurance for Pharmacy-Prepared Sterile Products in 1993.^{3,4} In 2002, the United States Pharmacopeia (USP) published an enforceable standard for pharmaceutical compounding of sterile preparations in Chapter <797>.⁵ Most recently, increasing concerns about the quality of compounded sterile preparations resulted in legislation that authorized the FDA to register “compounding outsourcing facilities” under Section 503B of the Federal Food, Drug, and Cosmetic Act.⁶

Compounding sterile preparations in a traditional way is an error-prone method, because it relies on the performance of humans.⁷⁻¹⁰ Robotics have the potential to improve accuracy and quality, as they are efficient in performing redundant tasks, such as preparing large numbers of sterile doses of medication. This study used a predictive modeling approach to estimate the potential cost savings based on reduced errors resulting from the use of an automated robotic technology. The robotic device evaluated in this project was *RIVA* (Intelligent Hospital Systems, Winnipeg, Manitoba, Canada).

The *RIVA* system prepares medications for syringes and intravenous (IV) bags in an aseptic environment using high-efficiency particle absorption (HEPA)-filtered air flow, positive air pressure containment, and continuous air quality monitoring within the compounding chamber of the robot situated in hospital central pharmacies. Negative air pressure configurations are used in the preparation of chemotherapy in order to prevent staff exposure to potentially dangerous cytotoxic medications. The system can be configured for general hospitals, cancer hospitals, infusion centers, and pediatric hospitals. Technicians load drug and diluent vials of inventory into the compounding chamber; the drugs are transferred within the chamber via sterile syringes that are pulsed with high-energy ultraviolet (UV) light to ensure disinfection of vial puncture sites. Drug identity is monitored with barcoding and volumetric weight checks are performed with electronic scales throughout the process. Final preparations are labeled in human- and machine-readable form to eliminate any re-labeling errors and to create a complete electronic audit trail.^{11,12}

METHODS

A probability pathway model estimated the cost impact of using a robotic technology to prepare sterile

doses of medications compared to a manual system. The probability pathway model is a mathematical way to simulate a physical process. It can produce an estimate of the number of flaws and intermediate outcomes in that process by applying known error frequencies at each step in the process and projecting the health impact of each error.

The probability pathway model for estimating errors during the compounding of sterile preparations was based on the steps used to compound sterile preparations. Ten discrete steps were identified based on the work of McDowell et al. For each step in this process, the potential for an error that could result in patient harm and increased health care costs was determined by a review of the literature of studies to identify the rate of such errors. The probability of contamination was added to the model, resulting in 11 points at which an error leading to an adverse event could happen during the preparation process. **Table 1** summarizes these errors, and their frequencies as have been reported.

To estimate the financial impact of using robotic technology to prepare sterile medications, we considered the following activity factors: average daily census, the number of doses prepared per day, the percentage of doses requiring drug-diluent reconstitution, the estimated cost of hospitalization per day, the percentage of errors increasing length of stay (LOS), the number of hospitalization days resulting from the adverse drug event, and the effectiveness of the robotic technology in producing error-free doses. **Table 2** summarizes these factors and the range of values that have been published. For adverse drug events, factors such as added treatments and transfer to an intensive care add to the cost¹³; for this simulation, reported daily hospital costs that include these factors were used.¹⁴⁻¹⁹ Hospital costs were adjusted to 2012 dollars using the gross domestic product (GDP) price deflator for inflation.²⁰ The cost of potential litigation, effects of reduced medical malpractice liability, and the reduced personnel cost from automation were not used in this simulation.

The robotic technology that was evaluated in this simulation was designed with a number of internal error checking and aseptic process features. When quality control measurements fall outside preset error bands, the sterile preparation is rejected and the process is halted for operator intervention. At this writing, the device has prepared more than 1.5 million sterile doses in a variety of hospital settings.²¹ Approximately 1% of these doses have been rejected

before process completion, because they do not meet quality parameters and are not dispensed. No errors or contaminated doses have been reported to reach any patients.²² This suggests a technology that is 100% effective, but experience suggests that nothing is absolutely perfect. When a new technology is introduced to an existing process, both the technology and the process undergo modifications that yield unintended outcomes.²³ Weaknesses have been discovered soon after the introduction of other health care technologies such as barcode medication administration (BCMA)

and computerized prescriber order entry systems (CPOE).²⁴ We have constructed this cost avoidance simulator with a 95% to 100% effectiveness range to account for the uncertainty of the technology's impact once it is more universally deployed.

Figure 1 portrays the calculation steps and information flow of the model. Each parameter affecting the number of errors (**Table 1**) and each factor used to estimate the financial impact (**Table 2**) has a range of possible values based on published studies. There is a very large range of outcomes possible when the

Figure 1. Probability pathway model for cost avoidance simulator. Ranges show the variation of that variable.

Table 1. Probability of errors at various steps in the admixture preparation process

Preparation step	Average error rate, % (range)	No. of observations	References
Obtain drug	1.8 (0.02–9.5)	51	7,9,38–52
Obtain diluent	2.0 (0.02–10.0)	52	7,8,9,38,41,43,53
Swab septum	2.1 (0.04–8.8)	48	9, 38,41,42,44,52,54
Draw diluent	2.0 (0.02–7.1)	50	9,38,41,52,54
Add diluent	2.0 (0.02–8.9)	49	9,38,41–43,45,52,54
Dissolve drug	2.1 (0.04–8.8)	50	9,38,41,42,44,49,51,52,54,55
Draw drug	2.0 (0.02–7.1)	54	9,38,41,42,44,53–55
Check dose	2.0 (0.02–8.8)	61	7,8,9,38,41–49,54,56–58
Label dose	2.0 (0.04–9.0)	46	9,38,41,44–46,48–52,55
Dose check	1.6 (0.02–8.5)	51	7,8,9,38,39,41,43,52,54,56
Contamination	3.0 (0.09–7.0)	12	50,59–62

Note: Values were used in risk simulation models to estimate the number of errors that can reach patients.

Table 2. Factors relating to the hospital setting that can affect the cost impact of medication errors during admixture preparation process

Model input	Average value (range)	No. of observations	References
Daily census	153 (18.6–400)	8	14,15,41,51,63
Doses per patient day	0.94 (0.171–1.942)	11	16,39–42,48,50,51
Share re-constituted	53.3% (40%–60%)	3	a, b
Percent of errors that increase length of stay	1.63% (0.1%–3.9%)	19	14,39,41,46,47,50,52,54,57,58,64
Length of stay increase, days	3.17 (1.74–5.4)	7	14–18
Percent of errors this technology can prevent	97.5% (95%–100%)	2	13,21,22
Daily hospital cost	\$1,355 (\$389–\$1,910)	13	14–18

Note: Values were used as inputs to the cost simulation model to estimate costs.

^aPersonal communication, Alex Reinhardt, Marketing Director, Intelligent Hospital Systems, June 2013.

^bPersonal communication, Craig Boyce, Pharmacists, Intelligent Hospital Systems, June 2013.

model inputs are varied. We addressed this issue by repeating the calculations many times using different randomly selected values with each repetition. The collection of outcomes from these repeated calculations represents both the range and likelihood of the physical process of sterile dose preparation, potential errors, and cost of those errors. The calculations shown in **Figure 1** were repeated 1,000 times, with all parameters of the model randomly selected on each repetition.

RESULTS

The results of these simulations are illustrated in **Figure 2**. Each dot represents one calculation outcome of sterile dose preparation errors (horizontal axis) and financial impact (vertical axis). The average of these 1,000 simulations is marked with an “X” at 5,420 errors prevented per year and \$288,350 of annual cost avoidance. The median of these 1,000 simulations is marked with a large black dot at 4,638 errors prevented per year and \$203,569 of annual cost avoidance.

Figure 2. Errors prevented and costs avoided in 1,000 simulations.

A one-way sensitivity analysis was conducted for each parameter used in the model to determine influential variables with the most impact on the results of the model. **Figure 3** shows the interquartile range for the selected parameter's effects on cost avoidance in the model. Vertical lines indicate the 25th to 75th percentile of cost avoidance resulting from 1,000 simulations of the model where only that parameter is varied. Taller vertical lines indicate which parameters have the greatest effect on cost avoidance. Cost avoidance results were most sensitive to contamination rates and share of errors causing LOS increases.

DISCUSSION

The true frequency and resulting cost of medication errors has been difficult to determine with accuracy. Observation-based studies can estimate the frequency of errors with some degree of accuracy, but the rate of adverse events resulting from these

errors is more challenging. The most commonly used approaches are the case-control method and chart review. It is known that the percentage of medication errors that result in adverse drug events is relatively low, perhaps as low as 1%.²⁵ It is even more challenging to determine the cost of these events, considering the low incidence of adverse drug reactions in smaller populations of patients, such as those seen in an individual hospital.

The line of causality in this model and ultimately in the decision to use automation for sterile dose preparation assumes that dose preparation errors lead to patient harm and costs to the hospital. This risk is attenuated by the hospital pharmacy experience of having errors reach patients but not cause any noticeable harm. These innocuous close calls cannot be relied on as a last line of defense; they should be incorporated in any realistic risk simulation. Consequently, the model does not produce a direct linear relationship between errors and costs. Instead,

Figure 3. Sensitivity of avoided cost to model parameter variation.

there is a positive correlation of the two that can be seen in the scatter diagram of **Figure 2**. The correlation between sterile dose preparation errors and costs is positive but weak (correlation coefficient of 0.679) because of the loose causality relating errors to patient harm. Some dosage errors are tolerated by patients and result in no additional care requirements or increased LOS. Errors that do cause harm result in a range of possible increased LOS, which in turn are priced at a range of possible costs. This reflects the complexity of the interacting factors that result in errors and determine the costs resulting from these errors. This supports using methods such as the probability pathway model to estimate the cost of illness.²⁶

Probability pathway models, decision tree models, and simulations are used on a variety of health care topics to determine the financial impact of an intervention when observational data are unavailable or impractical to collect. These include comparisons of competing drugs for a specific condition,²⁷⁻³⁰ comparison of new imaging technologies with improved diagnostic accuracy,³¹⁻³³ and evaluation of a novel procedure, practice guideline, practice model, or treatment.³⁴⁻³⁷

The results of this study are needed to determine the value of an investment in robotic sterile medication dose preparation technology versus alternative uses of financial resources in the health care system. A convenient way of informing this type of choice

is a break-even analysis. A net present value (NPV) calculation for a business investment determines whether the cost of the investment will be recouped by subsequent savings. Savings that are spread over a number of years are discounted by a reasonable interest rate to make them directly comparable to current outlays. In this study, the robotic technology requires an investment outlay in the first year, followed by a stream of annual savings in subsequent years. The matrix in **Table 3** shows the 5-year NPV of cost savings from a hypothetical \$1 million investment in robotic sterile medication dose preparation technology. Columns relate to hospital size (average daily census), and rows relate to acuity of care (sterile doses per patient per day). Cells with NPV less than zero are shaded and fall short of the 5-year break-even point. Hospitals in these cells should not invest in this technology on the basis of opportunity cost alone, but may do so for other reasons such as freeing pharmacist time to practice in clinical roles as proposed in the ASHP Pharmacy Practice Model Initiative (PPMI) goals. There are additional financial savings that were not included in these calculations. Costs incurred through the manual preparation of sterile doses, drug waste, breakage, and inventory control are among a few of these. Readers can locate a given hospital in this break-even matrix by determining which column best describes the size of the hospital in average daily census and determining

Table 3. Net present value of robotic technology in sterile dose preparation

Doses per patient per day	Average daily census							
	40	80	120	160	200	240	280	320
0.2	(\$828,830)	(\$748,565)	(\$668,304)	(\$588,039)	(\$507,778)	(\$427,516)	(\$347,252)	(\$266,990)
0.4	(\$748,565)	(\$588,039)	(\$427,516)	(\$266,990)	(\$106,464)	\$54,062	\$214,584	\$375,110
0.6	(\$668,304)	(\$427,516)	(\$186,729)	\$54,062	\$294,849	\$535,637	\$776,424	\$1,017,211
0.8	(\$588,039)	(\$266,990)	\$54,062	\$375,110	\$696,164	\$1,017,211	\$1,338,263	\$1,659,312
1	(\$507,778)	(\$106,464)	\$294,849	\$696,164	\$1,017,211	\$1,498,786	\$1,900,099	\$2,301,413
1.2	(\$427,516)	\$54,062	\$535,637	\$1,017,211	\$1,498,786	\$1,980,364	\$2,461,939	\$2,943,513
1.4	(\$347,252)	\$214,584	\$776,424	\$1,338,263	\$1,900,099	\$2,461,939	\$3,023,778	\$3,585,614
1.6	(\$266,783)	\$375,110	\$1,017,211	\$1,659,312	\$2,301,413	\$2,943,513	\$3,585,614	\$4,227,715
1.8	(\$186,729)	\$535,637	\$1,257,999	\$1,980,364	\$2,702,726	\$3,425,088	\$4,147,453	\$4,869,815

which row is applicable based on the number of sterile doses administered per patient per day. The cell in **Table 3** where the row and column intersect indicates whether this technology is fiscally appropriate for this hospital. A hospital with an average daily patient census of 100 can expect to prevent 3,244 medication errors per year through the use of an automated IV preparation device. The prevention of these errors would result in a cost avoidance of \$144,350 in direct medical costs.

One of the limitations of studies of this type is the difficulty in determining who benefits when the cost of health care is reduced. Ultimately, it is desirable to make the best use of the limited resources spent on health care. Perverse incentives exist in many parts of the health care system where daily room rates and fees for service payment models exist. When reimbursement is based on services provided, rather than outcomes, it is difficult to use cost savings that result from improvements in care to cost-justify investments in technologies that can improve efficiency and quality.

Another limitation of this study is that it evaluated only one robotic technology. There are many technologies available, and each of them has different features that create different potential error points and probabilities of error at each step in the process. Cost savings estimates from this simulation cannot be applied to other versions of this technology. Additional simulations and a study of similar technologies such as *IVStation* and *Intelli-FillIV* should be conducted as a continuation of this inquiry.

CONCLUSIONS

The use of a robotic device can reduce health care costs by preventing errors that can cause adverse drug events. Health care technology such as robotic preparation of sterile medication doses play a key role in improving care and patient safety, but one must always be aware of the opportunity costs of these investments. Resources spent in implementing a specific technology preclude expenditures on other innovations that might have a greater impact on patient outcomes.

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