Standard Drug Concentrations and Smart-Pump Technology Reduce Continuous-Medication-Infusion Errors in Pediatric Patients

Gitte Y. Larsen, MD, MPH‡; Howard B. Parker, PhD‡; Jared Cash, PharmD‡; Mary O’Connell, RN, BSN‡; and Mary Jo C. Grant, PNP, PhD∗

ABSTRACT. **Objective.** To determine if combining standard drug concentrations with “smart-pump” technology reduces reported medication-infusion errors.

**Design.** Preintervention and postintervention comparison of reported medication errors related to infusion therapies during the calendar years 2002 and 2003.

**Setting.** A 242-bed university-affiliated tertiary pediatric hospital.

**Intervention.** Change in continuous-medication-infusion process, comprising the adoption of (1) standard drug concentrations, (2) “smart” syringe pumps, and (3) human-engineered medication labels.

**Main Outcome Measures.** Comparison of reported continuous-medication-infusion errors before and after the intervention.

**Results.** The number of reported errors dropped by 73% for an absolute risk reduction of 3.1 to 0.8 per 1000 doses. Preparation errors that occurred in the pharmacy decreased from 0.66 to 0.16 per 1000 doses; the number of 10-fold errors in dosage decreased from 0.41 to 0.08 per 1000 doses.

**Conclusions.** The use of standard drug concentrations, smart syringe pumps, and user-friendly labels reduces reported errors associated with continuous medication infusions. Standard drug concentrations can be chosen to allow most neonates to receive needed medications without concerns related to excess fluid administration. *Pediatrics* 2005;116:e21–e25. URL: www.pediatrics.org/cgi/doi/10.1542/peds.2004-2452; rule of six, intensive care unit, children, patient safety, medication errors.

Medication errors are a major source of potential and actual harm in pediatric patients.1–3 Pediatric patients are at greater risk for medication error than adult patients because of the need for weight-based dosing and individualized dose calculation for most medications. Effective communication about symptoms and elicitation of pertinent clinical findings is often difficult in children.2,4 Medical complexity and the need for multiple medications places hospitalized children at an even greater risk; nowhere is this more evident than in intensive care units.2–5 Continuous medication infusions are a category of medications delivered to hospitalized patients that often include “high-alert” medications. As defined by the Institute of Safe Medication Practice, high-alert medications are drugs that bear a heightened risk of causing significant patient harm when used in error and may lead to devastating complications for patients.6 The process of ordering, preparing, and administering continuous medication infusions offers several opportunities for error.4,7–9 Providing the correct weight-adjusted dose (at an acceptable rate, concentration, and volume) usually requires a multivariable calculation; moreover, a new calculation must be performed whenever the dose is changed. The need for individualized concentrations makes drip preparation a high-frequency and time-consuming task for the pharmacy. The appropriate information must be entered correctly into the pump initially and when changes are made.

Several common practices influence the likelihood of continuous-medication-infusion errors. The “rule of 6” is a calculation aid that was developed originally to facilitate rapid dose calculation and drip preparation in emergency situations but is now in general use. The rule states that the dose (µg/kg per min) equals the rate (mL/hour) when the concentration is prepared according to the following formula: 6 × patient weight (kg) = amount of drug (mg/100 mL).10 The use of standard drug concentrations eliminates the need to prepare a large number of individualized concentrations.11 However, facilities that use standard drug concentrations must then rely on dosing charts, which are tables of precalculated values, to reduce the need for calculations. Recently, “smart-pump” technology has become available. Smart pumps incorporate sophisticated computer technologies for storing drug information (ie, drug library), making calculations, and checking entered information against dosing parameters (ie, safety net).12 Advantages and disadvantages of these approaches are summarized briefly in Table 1; however, there is no consensus among providers regarding the optimal practice to limit medication errors associated with continuous medication infusions while providing acceptable fluid volumes in pediatric patients.13

This study evaluated whether 3 concurrent changes in practice—standard drug concentrations, smart syringe pumps, and redesigned labels—would decrease reported errors associated with continuous medication infusions.
METHODS

The setting for this preintervention and postintervention study was Primary Children’s Medical Center (Salt Lake City, UT), a 242-bed university-affiliated tertiary pediatric hospital. Before the intervention, the continuous-medication-infusion process consisted of the following steps: (1) orders were handwritten by clinicians either as free text or directly onto preprinted infusion sheets and sent to the pharmacy; (2) pharmacists entered data into a computer that calculated, based on the rule of 6, individualized “recipes” for mixing concentrations; (3) the infusion was mixed and delivered to the units with dosing charts specific to that concentration; and (4) the nurses either used the dosing charts to determine the appropriate infusion rate or made the rate calculation by hand and then programmed the infusion rate into the pumps.

The intervention consisted of 3 changes to this process. First, standard concentrations were developed for 32 common medications delivered by intravenous continuous infusion (Table 2). These medications collectively make up ~95% of the medications in the hospital infused continuously via syringe pumps. For each medication, the choice of concentration was based on available commercial concentrations, standard drug concentrations surveyed from 10 other pediatric facilities, and an analysis of past usage at our facility. To verify that these standard concentrations were appropriate in the NICU, we looked at the range of concentrations prepared by the rule of 6 over a 2-week period and then matched the standard concentrations to that range. Depending on the infusion drug, we determined that between 1 and 4 standard concentrations met the fluid requirements of most of our patients.

Second, a multidisciplinary task force consisting of nursing, pharmacy, clinical engineering, physicians (neonatologist, pediatric intensivist, cardiothoracic surgeon, and anesthesiologist), and

<table>
<thead>
<tr>
<th>Medication</th>
<th>Concentration 1</th>
<th>Concentration 2</th>
<th>Concentration 3, 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amiodarone</td>
<td>2 mg/mL</td>
<td>6 mg/mL</td>
<td></td>
</tr>
<tr>
<td>Aprotinin</td>
<td>1.4 mg/mL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dobutamine</td>
<td>1 mg/mL</td>
<td>4 mg/mL</td>
<td></td>
</tr>
<tr>
<td>Dopamine</td>
<td>0.8 mg/mL</td>
<td>3.2 mg/mL</td>
<td></td>
</tr>
<tr>
<td>Epinephrine</td>
<td>8 µg/mL</td>
<td>64 µg/mL</td>
<td></td>
</tr>
<tr>
<td>Esmolol</td>
<td>10 mg/mL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fentanyl</td>
<td>10 µg/mL</td>
<td>50 µg/mL</td>
<td></td>
</tr>
<tr>
<td>Furosemide</td>
<td>1 mg/mL</td>
<td>10 mg/mL</td>
<td></td>
</tr>
<tr>
<td>Heparin</td>
<td>50 U/mL</td>
<td>100 U/mL</td>
<td></td>
</tr>
<tr>
<td>Hydromorphone</td>
<td>1 mg/mL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insulin</td>
<td>0.1 U/mL</td>
<td>1 U/mL</td>
<td></td>
</tr>
<tr>
<td>Isoproterenol</td>
<td>8 µg/mL</td>
<td>64 µg/mL</td>
<td></td>
</tr>
<tr>
<td>Ketamine</td>
<td>10 mg/mL</td>
<td>100 mg/mL</td>
<td></td>
</tr>
<tr>
<td>Lidocaine</td>
<td>4 mg/mL</td>
<td>8 mg/mL</td>
<td></td>
</tr>
<tr>
<td>Midazolam</td>
<td>1.0 mg/mL</td>
<td>5 mg/mL</td>
<td></td>
</tr>
<tr>
<td>Milrinone</td>
<td>200 µg/mL</td>
<td>400 µg/mL</td>
<td></td>
</tr>
<tr>
<td>Morphine</td>
<td>1 mg/mL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitroprusside</td>
<td>400 µg/mL</td>
<td>1 mg/mL</td>
<td></td>
</tr>
<tr>
<td>Norepinephrine</td>
<td>8 µg/mL</td>
<td>64 µg/mL</td>
<td></td>
</tr>
<tr>
<td>Pancuronium</td>
<td>1 mg/mL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phenytoin</td>
<td>50 µg/mL</td>
<td>100 µg/mL</td>
<td></td>
</tr>
<tr>
<td>Potassium</td>
<td>0.2 mEq/mL</td>
<td>1 mEq/mL</td>
<td></td>
</tr>
<tr>
<td>Procainamide</td>
<td>4 mg/mL</td>
<td>8 mg/mL</td>
<td></td>
</tr>
<tr>
<td>Propofol</td>
<td>10 mg/mL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prostaglandin</td>
<td>5 µg/mL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Remifentanil</td>
<td>25 µg/mL</td>
<td>50 µg/mL</td>
<td></td>
</tr>
<tr>
<td>Sodium bicarbonate</td>
<td>1 mEq/mL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sufentanil</td>
<td>0.5 µg/mL</td>
<td>1 µg/mL</td>
<td>5 µg/mL, 10 µg/mL</td>
</tr>
<tr>
<td>Terbutaline</td>
<td>1 mg/mL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tranexamic acid</td>
<td>5 mg/mL</td>
<td>10 mg/mL</td>
<td>25 mg/mL, 50 mg/mL</td>
</tr>
<tr>
<td>Vasopressin</td>
<td>0.025 U/mL</td>
<td>1 U/mL</td>
<td></td>
</tr>
<tr>
<td>Vecuronium</td>
<td>2 mg/mL</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
the hospital safety manager developed criteria to select a smart syringe pump (Table 3). Once a syringe pump that met all criteria was identified (Medex, Carlsbad, CA), 340 pumps were purchased. The smart pump included a modifiable drug library from which the practitioner could choose the drug to be administered. The smart pump calculated the rate of administration, providing an alert if the dose entered exceeded the limits of the safety net, and provided a clear visual display of the drug, dose, and rate being infused. The task force determined the appropriate drugs and dosing ranges for the drug library. The dosing ranges were individually selected for each drug with the intent to avoid 10-fold overdoses.

Third, pharmacy-generated medication labels were changed to facilitate the correct transfer of information from the label to the pump (Fig 1), which involved using human-factor principles to separate the information that needed to be entered into the pump from other information, highlighting this information, and formatting the label to match the pump programming.

This entire process of development occurred over the course of 1 year. The 3 changes were implemented throughout the hospital over a 1-week period. Education of staff began during the week before and continued throughout the week of implementation. We used a “train-the-trainer” approach. Each class lasted 1 hour with up to 8 to 10 attendees per class. Each hospital unit had a trained clinician available on the day of implementation to answer questions and address issues. The pump manufacturer also made available clinical and technical support during the implementation week.

The main measurement outcome was reported errors associated with continuous medication infusions captured by the hospital’s incident-reporting system. After the changes had been in place for 1 calendar year, errors reported for the 12-month period before the change (2002) were evaluated retrospectively and compared with errors reported during the 12-month period after the change (2003). All reported medication errors from this 2-year period were reviewed. A reported incident was considered a continuous-medication-infusion error if and only if it involved 1 of the 32 standardized medications and an infusion pump (patient-controlled analgesic pumps were excluded).

A 2-sample test of proportions was used to calculate the difference in error-reporting rates before and after the intervention. The change in error rate and corresponding 95% confidence interval were calculated. Data analysis was performed with Minitab 13.20 (State College, PA). The University of Utah Institutional Review Board granted approval for this study.

RESULTS

After the interventions, there was a 73% reduction in the number of reported errors associated with continuous medication infusions. Specifically, the error rate decreased from 3.1 to 0.8 per 1000 doses for an absolute risk reduction of 2.3 errors per 1000

Preintervention

<table>
<thead>
<tr>
<th>JOHN DOE</th>
<th>Bed: NB</th>
<th>wt: 2kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>FENTANYL (PD* 0.01mg/ml, D5W)</td>
<td>Medication Concentration = 0.01mg/ml</td>
<td></td>
</tr>
<tr>
<td>Dose = 1 mcg/kg/hr @ Flow Rate 0.2ml/hour</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diluent (s) : D5W</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Volume Dispensed = 15ml</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dispensed: 01/14/2003</td>
<td>Expires: 01/15/2003 @ 1300</td>
<td></td>
</tr>
</tbody>
</table>

Postintervention

<table>
<thead>
<tr>
<th>JOHN DOE</th>
<th>Bed: PCMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Med: FENTANYL</td>
<td></td>
</tr>
<tr>
<td>Conc.: 0.01 mg/ml</td>
<td></td>
</tr>
<tr>
<td>Weight: 2 kg</td>
<td></td>
</tr>
<tr>
<td>Total Volume Dispensed: 15ml</td>
<td></td>
</tr>
<tr>
<td>Dose: 1 mcg/kg/hr</td>
<td></td>
</tr>
<tr>
<td>Flow Rate: 0.2ml/hour</td>
<td></td>
</tr>
<tr>
<td>Diluent: D5W</td>
<td></td>
</tr>
</tbody>
</table>

Fig 1. Pharmacy-generated labels for continuous medication infusions.

We found a significant decrease in reported errors involving continuous medication infusions in pediatric patients after implementation of standard drug concentrations, smart syringe pumps, and human-engineered medication labels to guide practitioner pump programming. The substantial reduction in reported errors may be attributed to several factors.

1. The use of standard drug concentrations reduces the number of individual concentrations prepared and the number of preparation steps. Both these reductions translate to fewer opportunities to make errors, and we found a reduction from 8 to 2 reported preparation errors.

2. The smart pumps shift the calculation burden from practitioners and pharmacists to computers. The smart pump also allows practitioners to change the dose directly, without the need for any intervening calculation. The drug libraries within the smart pump automatically default to the appropriate concentration and measurement units (milligrams, micrograms, or units) when the medication is selected, which reduces the likelihood of confusing units, and eliminates the need to make unit conversions. The built-in safety net alerts the practitioner when the entered dose exceeds preprogrammed limits and requires a deliberate override to continue. The pump display provides a complete and accurate account of what is being delivered to the patient, which provides the practitioner with feedback about the correctness of their information entry and facilitates double-checks.

The primary source of information to be pro-

TABLE 3. Smart-Pump Selection Criteria

| 1. Accuracy: must pass clinical engineering bench testing |
| 2. Intuitiveness of programming |
| 3. Safety Net: high- and low-dose programming parameters |
| 4. Drug library: modifiable and hospital generated to meet institutional needs |
| 5. Dose-rate calculator within the pump |
| 6. Size: small enough to fit numerous pumps on intravenous line pole; request to be able to clamp pump to warmer in NICU |
| 7. Syringe size: 1–60 mL from various manufacturers |
| 8. Alarms: must be audible and visible |
| 9. Rotating pole clamp: allow pump to be vertical or horizontal |
| 10. Durability |
| 11. Serviceability |
| 12. Compatible with electronic charting |
| 13. MRI compatible: can be taken into the scanner if necessary |
STANDARD CONCENTRATIONS AND SMART PUMPS REDUCE ERRORS

A combination of standard drug concentrations, smart-pump technology, and human-engineered medication labels reduced reported errors associated with continuous medication infusions in hospitalized pediatric patients. The use of new technology allows health care providers working in medically complex environments to provide safer patient care. Ideal implementation would include development of standardized staff-education programs with scenario-based evaluation of smart-pump technology, a national consensus of standardized drug concentrations for pediatric patients, an interface with computerized order entry systems and electronic charting, and rigorous error-detection and -reporting systems.

CONCLUSIONS

We thank Marc Holley, RPh, and Mark MacKay, RPh, for considerable work in determining standardized drug concentrations and tireless efforts to promote the adoption of standard drug concentrations and computerized order entry systems.

ACKNOWLEDGMENTS

There are several limitations to this study. The primary data for this study were generated by the hospital-wide incident-reporting system. Incident reports have been demonstrated to underreport errors. Nevertheless, consistent incident reports are a reasonable measurement of the relative number of errors. Because the absolute number of incident reports varied little throughout the study period, the decrease in errors can reasonably be attributed to the interventions. There were no apparent temporal trends in error rate. Error occurrence seemed to be random during both the preintervention and postintervention periods. The 3 interventions were introduced as a package, making it impossible to determine the extent to which each individual intervention contributed to the reduction in error. We cannot rule out the possibility that increased awareness and vigilance due to staff education may have contributed to the reduction in errors, but we are aware of no other organizational factors that might have contributed to the reduction. Three of the 37 preintervention events and 1 of the 10 postintervention events resulted in patient harm. The low frequency of harm makes it impossible to draw robust conclusions about the impact of the intervention on patient harm. However, the reduction in 10-fold dosing errors strongly suggests a trend toward increased safety.

Although the number of reported incidents involving continuous medication infusions is small, the true error rates might be much higher.4 These errors often involve the delivery of high-alert medications to seriously ill patients, which makes it particularly important to minimize this type of error. We found a significant reduction in reported errors associated with continuous medication infusions; as a result, patient safety improved.

To maintain the gains in patient safety, we continued to provide education periodically on correct pump usage, added more drugs to the available standard drug concentration list, increased the usage of standard drug concentrations in the NICU, conducted an iterative process to improve the smart-pump software, and expanded the usage of the smart pumps for other noncontinuous medication infusions (eg, intralipids, electrolytes, and antibiotics).

TABLE 4. Errors Reported for the 12-Month Period Before and After the Intervention

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Unit</th>
<th>No. of CMIs</th>
<th>No. of Errors</th>
<th>No. of Ordering Errors</th>
<th>No. of Preparation Errors</th>
<th>No. of Administration Errors</th>
<th>No. of ≥10-fold Overdose</th>
<th>Error Rate per 1000 Doses</th>
<th>% Standard Drug Concentrations of All CMIs Prepared</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preintervention</td>
<td>PICU</td>
<td>7527</td>
<td>21</td>
<td>12</td>
<td>8</td>
<td>28</td>
<td>5</td>
<td>2.8</td>
<td>0</td>
</tr>
<tr>
<td>period (2002)</td>
<td>NICU</td>
<td>3431</td>
<td>12</td>
<td>12</td>
<td>4</td>
<td>28</td>
<td>5</td>
<td>3.5</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>1151</td>
<td>4</td>
<td>12</td>
<td>1</td>
<td>28</td>
<td>5</td>
<td>3.5</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>12109</td>
<td>37</td>
<td>12</td>
<td>8</td>
<td>28</td>
<td>5</td>
<td>3.1</td>
<td>0</td>
</tr>
<tr>
<td>Postintervention</td>
<td>PICU</td>
<td>7520</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>28</td>
<td>5</td>
<td>0.7</td>
<td>&gt;99</td>
</tr>
<tr>
<td>period (2003)</td>
<td>NICU</td>
<td>3620</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>28</td>
<td>5</td>
<td>1.4</td>
<td>87</td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>1259</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>28</td>
<td>5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>12399</td>
<td>10</td>
<td>10</td>
<td>2</td>
<td>28</td>
<td>5</td>
<td>0.8</td>
<td>2.3*</td>
</tr>
</tbody>
</table>

CMIs indicates continuous medication infusions.
* P < .001.
concentrations throughout the hospital. We thank Amy E. Donaldson, MS, and the Intermountain Injury Control Research Center for assistance with statistical analysis.

REFERENCES
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