Medication errors are commonly associated with i.v. and high-risk medications that may cause severe patient harm.\textsuperscript{1–4} Smart infusion pumps improve the safety of i.v. medication administration by providing customizable libraries with dose limits and administration rates specific to medications and care areas.\textsuperscript{5,6} Alerts are generated when infusions are programmed outside the individualized limits, and users can either reprogram the infusion or override the alert and continue medication administration as originally programmed. A national survey of pharmacy practices in hospital settings reported the use of smart infusion pumps in 77\% of U.S. hospitals.\textsuperscript{7} Although smart pumps have been widely adopted, their effectiveness has been questioned. One trial evaluating the use of smart pumps in a cardiac surgery unit at an academic medical center did not identify a decrease in serious medication administration errors with the use of smart pumps.\textsuperscript{8} Smart-pump technology captures extensive, detailed data on each alert generated that can be reported for

**Purpose.** A Web-based analytics system for conducting inhouse evaluations and cross-facility comparisons of alert data generated by smart infusion pumps is described.

**Summary.** The Infusion Pump Informatics (IPI) project, a collaborative effort led by research scientists at Purdue University, was launched in 2009 to provide advanced analytics and tools for workflow analyses to assist hospitals in determining the significance of smart-pump alerts and reducing nuisance alerts. The IPI system allows facility-specific analyses of alert patterns and trends, as well as cross-facility comparisons of alert data uploaded by more than 55 participating institutions using different types of smart pumps. Tools accessible through the IPI portal include (1) charts displaying aggregated or breakout data on the top drugs associated with alerts, numbers of alerts per device or care area, and override-to-alert ratios, (2) investigative reports that can be used to characterize and analyze pump-programming errors in a variety of ways (e.g., by drug, by infusion type, by time of day), and (3) "drill-down" workflow analytics enabling users to evaluate alert patterns—both internally and in relation to patterns at other hospitals—in a quick and efficient stepwise fashion.

**Conclusion.** The formation of the IPI analytics system to support a community of hospitals has been successful in providing sophisticated tools for member facilities to review, investigate, and efficiently analyze smart-pump alert data, not only within a member facility but also across other member facilities, to further enhance smart pump drug library design.

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analysis and evaluation of practice patterns. Routine analysis of pump alerts and adjustments in drug libraries can minimize nuisance alerts, minimize the need for nursing staff workarounds, and maximize the safety of medication administration.\textsuperscript{9,10} Reviewing, analyzing, understanding, and acting on smart-pump data are critical components of improving patient safety in the administration of i.v. medications.

Different smart-pump manufacturers provide analytic tools that vary in quality and quantity. Even the basic charts, reports, and metrics provided by higher-quality tools for investigating captured smart-pump alert data can be time-consuming to analyze. In addition, all analytic tools provided by pump manufacturers are restricted to analysis of data from a single institution, with no opportunity for data sharing and collaborative learning.

The Infusion Pump Informatics (IPI) system provides advanced analytics and tools for investigative workflow analysis that have been developed in collaboration with hospital pharmacists and other medication safety analysts in the IPI community. Members of this community use IPI for sophisticated analytics—not only for investigating data from their own institutions but also for investigating and comparing data from all hospitals participating in the IPI project. The IPI system and its user community together offer a method to standardize investigation and assessment, since data captured by smart pumps of different manufacturers and from different hospital systems are available for simultaneous investigation and comparison by all IPI-participating hospitals.

Background

In early 2009, the IPI system was launched as a comparative database, with a Web-based interactive environment, for analyzing and reporting on smart-pump alert data. Two Indiana hospitals were the first IPI community members and provided alert data generated by their smart-pump systems (Alaris, CareFusion Corporation, San Diego, CA) for upload and secure storage in the IPI database. Medication safety analysts from each institution were then provided full access to investigate alerts and compare data across both hospitals. At the time the IPI system was launched, it was already unique in many important ways: It offered a Web-based portal allowing any number of authorized users to access and analyze alert data from any browser; it stored alert data from more than one hospital system and provided a consistent, universal interface that managed the presentation and selection of hospital-specific data (e.g., drugs, care areas, drug libraries) in a user-friendly way; it offered charts and reports in a Web environment; and it allowed analysts at the two Indiana hospitals to study data from each other’s institution and compare data between hospitals on the same charts. Furthermore, the IPI system was built on a collaborative Web platform that offered discussion forums and group spaces so that the hospitals could communicate with each other and with the IPI development team. The key development concept for the IPI system was for developers to work closely with hospital analysts to design new features and support the workflow analytics they needed to study the alert data and improve the effectiveness of the infusion pumps.

The IPI community has grown at a controlled rate and today has members from 30 hospital systems comprising a total of 55 hospitals across six states. The IPI system now supports the upload of captured alert and compliance data from both CareFusion and Hospira smart pumps (Hospira, Inc., Lake Forest, IL), with additional manufacturer support under development. Uploaded data generated at multiple hospitals by pumps of multiple makes and models are stored together within the same structures in the IPI database. The database structures are designed to serve as a standard representational framework that unifies all captured pump data across all manufacturers. The same user-friendly, consistent, and universal interface allows hospitals to access and analyze smart-pump data from any IPI-participating hospital and compare important metrics from any or all hospitals on the same charts.

Analysis and resolution

The comparative and investigative workflow analytics offered by the IPI system are designed as flexible, extensible building blocks made up of selectable variable sets (e.g., drugs, care areas, alert types) and “clickables” (charts and reports that link to each other through the parameters). From the IPI dashboard, users enter different analytic areas where they can study alerts in different ways (Figure 1). These areas are described below.

Analysis Charts. IPI Analysis Charts offer both aggregated and breakout data, enabling users to study alert totals and trends so they can identify medications consistently associated with alerts and detect trends in alerts after drug library changes. Before users choose a chart, they select from important options that control and filter the data to be displayed, making it easier to target specific alerts. All Analysis Charts can be generated using any combination of user-selectable options, such as hospitals, facilities, care areas, drugs, fluids, time period, versions of the drug libraries, action taken (override, reprogram, or cancel), infusion types (e.g., continuous, bolus), and alert type (e.g., field limit). Users generally begin an IPI session with their own hospital, the current month or quarter, and most options set to “all.” The technology allows for the end user to easily “drill down,” or delve further into, the data without needing to
Figure 1. The Infusion Pump Informatics (IPI) dashboard, the gateway to smart-pump alert analytics and IPI community data sharing.
manually open additional records. This results in the user being able to quickly identify facilities, care areas, or drugs of concern.

One commonly used collection of IPI charts includes charts on “top drugs” (i.e., those associated with the highest numbers of alerts); a series of monthly trend charts with stacked bars showing alert contributions by facility, care area, action taken, or infusion type; and a series of time-of-day stacked bar charts. IPI “ratio charts” depict monthly trends for alerts per device, override-to-reprogram ratios, and overrides as a percentage of total alerts; these ratios provide critical measures of the effectiveness of the hospital drug-limit libraries. Also, since ratio charts display normalized data, they offer excellent metrics for comparing hospitals of very different sizes and pump populations. The IPI pie chart collection includes breakdowns of alert totals by care area, infusion type, and field limit type. A collection of “time-to-override” charts was added recently for the study of alert fatigue. A period of two seconds (or less) is considered too short for nurses to properly respond to an alert; overrides within that time frame are regarded as indicative of nursing staff “ignoring” alerts. Time-to-override charts include the monthly trend for alerts with alert-to-override intervals of two seconds or less, as well as a frequency distribution graph showing the number of alerts and specific override times in seconds. Hospitals can conduct studies of time delays associated with alert overrides, including investigations focused on specific drugs and care areas. Hospitals can also study how the frequency distribution changes over time and, thus, how effective drug library changes are in controlling override times of two seconds or less.

Analysis Charts provide a graphic way to identify alert totals in aggregate or by drug and care area. Moreover, the IPI technology has workflow support capabilities that allow users to click on peaks in charted data where they want to drill down and investigate in detail, as described below.

IPI Investigative Reports. The IPI system’s Investigative Reports tools offer spreadsheet-style tabular tools for reviewing detailed alert information. Users choose from a collection of searchable tabular reports and can select options that control and filter the data presented (e.g., by time range, by drug, by care area). Each row in the report describes one alert, displaying the full set of data captured by the smart pump for that alert: hospital, facility, care area, drug, infusion therapy type, programmed value, limit library used, drug limit, hard or soft limit, above or below limit, “times limit” (described below), time stamp, device identifier, action taken, and other infusion- and limit-specific data such as diluent volume, volume to be infused, drug amount, infusion rate, and infusion duration.

The times-limit descriptor is a multiplier indicating the degree to which the programmed value was over or under the library-specified limit; for example, a value of 10 means the quantity entered by the nurse was 10 times the specified limit for a given drug. The times-limit feature is particularly valuable in helping IPI system users better understand the meaning of alert overrides. Overrides that are in the “10 times” range may often involve decimal-entry errors by a pump user. Overrides that are much smaller may help better define a drug library limit that may be set too narrowly and contribute to alert fatigue.

Each report column has a search box that, when clicked, brings up a list of data filters. This feature is useful for seeing which drugs or care areas are listed in reports and how often they are listed. All report columns can be sorted, searched, and filtered, so users can immediately winnow the alert rows to focus on areas of concern.

Users can generate searchable reports for “good-catch” or “missed-catch” alert events. For good-catch reports, the IPI system displays data on alerts for large-percentage pump programming errors to which the nurse responded by reprogramming the infusion—e.g., the nurse reprogrammed the pump after initially entering a value 10 times the maximum allowable library limit for a particular drug; in this case, the smart pump’s alerting function would be considered to have made a good catch. The good-catch report lists these alerts, sorted by times limit in descending order of magnitude, and graphs are available to show the programmed and reprogrammed values alongside the library limit that triggered the alert. These reports and graphs are valuable for evaluating the effectiveness of limit-setting and alert-generation functions. In contrast, missed-catch reports present information on events in which an alert was triggered but a nurse overrode the alert and proceeded with the infusion as initially programmed. Analysts look for drugs or care areas frequently cited in missed-catch reports and investigate cases involving large-percentage infusion errors. The information in the report can be used to identify when and under what circumstances these infusions occurred.

IPI Pivot Charts. Among other analytics accessible within the Pivot Charts area of the IPI system are “pivot tables”: special statistical tools that let users examine alert counts in ways that provide insights on how nurses are programming infusions. Users select a drug, a care area, a particular time period, and a particular limit library and then generate a bar chart showing all values programmed by nurses that were outside the library limits (on the x-axis) and how many alerts were generated at each value (the height of the bar chart on the y-axis). Users can analyze the degree to
which programmed infusion values correspond to or deviate from drug library–specified limits. They can identify which programmed values are associated with the largest numbers of alerts and whether nurses are overriding most of the alerts generated when programmed values are close to existing limits. Through the use of these charts, IPI system users have learned that a small extension of an existing limit can lead to a large decrease in the number of associated alerts. When users click on a bar for a particular programmed value, an investigative report on alerts programmed at that value is launched, providing information on how many of the alerts were overridden, which pumps generated the alerts, and other details. IPI system users generally click on the highest bars in the pivot chart in order to investigate programmed values associated with the greatest numbers of triggered alerts.

**Drill-down workflow analysis.** When users start an IPI session, they often request a workflow display sequence that begins with aggregate charts (e.g., top 10 drugs associated with alerts) and then systematically drill down, or pull data from the next level of information to look at detailed investigative reports for more information about those drugs. The IPI system has a “clickable charts” drill-down feature that allows users to click on bar charts and sectors in pie charts to explore and understand all details corresponding to alerts of interest. The workflow display allows users to understand all the conditions associated with a drug’s top-10 status: Which care areas, devices, and infusion types were involved? What actions were taken? What values were programmed, and how close to (or far from) the library-specified drug limits were those values? The goal is to determine (1) whether library limits for the drug should be changed, (2) whether nurse education on proper infusion of the drug is needed, (3) whether the medication name should be clarified to prevent confusion between medications to be administered via intermittent versus continuous infusion, and (4) whether new policies or procedures for medication safety should be instituted. An example of this type of workflow analysis is described below and illustrated in Figure 2.

**Step 1.** The user creates a top-10 chart for drugs associated with alerts in critical care areas, using data filters to request information for the third quarter of 2013 and the drug-limit library released in August 2013.

**Step 2.** The top three alert-generating drugs in critical care units are propofol (204 alerts), vancomycin (158 alerts), and hydromorphone (104 alerts). Clicking on propofol provides several follow-on charts, including “actions taken” and “field limit types” breakdowns. Clicking on the “actions taken” chart for propofol shows that nursing staff overrode 150 of 204 alerts, with similar statistics for vancomycin (114 of 158 alerts overridden) and hydromorphone (90 of 104 alerts overridden). The user then drills down on hydromorphone, since it has the highest override ratio.

**Step 3.** The user may now click on the menu item “Field Limits (Pie Chart)” for hydromorphone to see the infusion types breakdown. By far, the largest alert generator is the field limit “PCA [patient-controlled analgesia] max limit,” accounting for 52% of alerts; the user can click that sector of the pie chart to access the corresponding pivot table.

**Step 4.** In the pivot table, the user sees every alert-generating hydromorphone dose programmed by the nurses in critical care units during the period October–December 2013 and controlled by the August 2013 limit library. The limit library soft-alert maximum (3.0 mg) is marked on the pivot table. The alert-generating doses range from 3.2 mg (1 alert) to 13.2 mg (2 alerts). There were 17 alerts at a programmed dose of 6.0 mg, and 18 alerts at a programmed dose of 8.0 mg. Note that it takes only three clicks to go from the top-drugs report to the pivot table for the selected drug.

**Step 5.** The user may want to drill down to investigate 17 hydromorphone alerts in critical care units. Clicking on the bar in the pivot chart for the 6-mg dose launches a detailed investigative report showing all pump-captured data for these alerts, including time stamps, device identifiers, infusion details, and actions taken. Of the 17 alerts, 16 were overridden. At this point, the user may also click on the pivot bar for the programmed dose 13.2 mg (2 of 2 alerts overridden).

Other IPI workflow analyses accessible via the “click to drill-down” feature are available, such as the “alerts by month” chart, from which users can drill down for a selected month to access other charts (e.g., alerts by day, alerts by profile, “top drugs”). The main goal of these investigative workflow analyses is to provide hospitals with a path for discovering drug-alert issues in a way that is extremely efficient and effective. Workflows maximize what can be discovered in a minimal amount of time, allowing hospitals to move forward from analyzing data to taking action and assessing outcomes.

The IPI development team has continued to work hand in hand with the IPI community of hospitals to understand users’ needs. Individual hospital requests have prompted the development of unique and powerful IPI features and workflows. All reports and charts can be generated for any hospital, regardless of pump manufacturer. IPI even makes it possible for hospitals that switch from one pump manufacturer’s product to another product to maintain their analysis of all data captured from both pump types in the same charts, so that the impact of the change, as well as ongoing differences in trends, can continue to be studied.
Sharing data and knowledge. The IPI system is accessed by authorized users online (https://catalyze.care.org/ipi). IPI is built on HUBzero, a freely available open-source Web-based platform supporting collaborative research and education. HUBzero was created through a research project at Purdue University and funded by the National Science Foundation. The IPI community takes advantage of many features of the HUBzero platform to collaborate with one another and to communicate with the IPI development team. Invite-only “group spaces” can be established on HUBzero, offering members a secure space with a discussion forum, a wish list, a wiki, an events calendar, and more. In the group space for IPI, users ask ques-

![Figure 2. The illustrated investigative workflow analysis of smart-pump alert data for critical care areas begins with creation of a chart (upper left) showing the top 10 drugs associated with alerts (per the drug-limit library released in August 2013) during the fourth quarter of 2013. From that chart, the user clicks on the bar for hydromorphone (1) to drill-down to a pie chart (upper right) depicting alert frequency by field limit type (e.g., continuous dose, bolus dose, patient-controlled analgesia [PCA]). By clicking on the “PCA max limit” wedge (2), the user can access a pivot chart (lower left) showing the total number of programmed hydromorphone doses that triggered the PCA max limit alert. The user then clicks on the most prominent bar (3), representing 18 alerts for programmed doses exceeding the 6-mg limit, to drill down to an investigative report (4), which can be searched and filtered to analyze a wide range of detailed alert data.](image-url)
tions, and the community responds. The wish list is a means of communication between the community and the IPI developers; any IPI group member can enter a request for a new feature, and the IPI developers respond. Requests are evaluated for community priorities and level of development effort. In the past two years, 40 items have been requested by users, with the vast majority now included in the IPI system.

Because fast and easy cross-hospital comparative analysis is a major goal of IPI data sharing, the IPI system provides a “basic” comparison capability that allows users to select any number and combination of hospitals—even those using different pump manufacturers’ devices—and generate any standard, pie, or ratio chart. Since hospitals differ in care areas, drugs, infusion types, and actions taken, IPI sets these variables to “all” for basic cross-hospital comparisons; this removes the analytic complexities posed by (1) differences in numbers and names of care areas, (2) differences in names, tall-man lettering, and concentrations and doses for drugs, and (3) differences in infusion types and actions taken across hospitals and manufacturers. In this manner, users can compare hospitals using alert totals, trends, patterns, peaks, and normalized ratios (an especially valuable tool).

Two types of ratio charts are heavily used by the IPI community for conducting comparisons. The first type is the “compliance chart,” which identifies the percentage of infusions delivered within the control parameters of the drug-limit library. This is a critical number for medication safety: Unless the infused drugs are within the limit library, alerts will not be generated, and data will not be captured. A recently generated chart of monthly compliance percentages for all IPI hospitals showed a number of hospitals above 90%, some hospitals in the 70–90% range, and a few hospitals below 70%. The stark presentation of the percentages and their changes over time gives hospitals much to interpret and discuss. One of the IPI hospitals with consistently high compliance percentages presented a seminar to the IPI community on methods and policies it used to promote compliance.

The other critical comparison chart is the “override-to-reprogram” chart, which identifies the ratio of the number of override alerts to the number of reprogram alerts. IPI-participating hospitals usually fall into groups. One group has ratios that are close to, or even below, 1.0—which means the number of overrides is equal to or less than the number of reprograms; to date, these hospitals have generally been users of Hospira pumps, and the IPI community is now investigating manufacturer-related smart-pump operation, flexibility, limit library issues, and other possible factors to understand this association. Most hospitals have override-to-reprogram ratios between 3.0 and 8.0, with a few hospitals at 11.0 and higher. The trends over time are instructive, as hospitals adjust limit libraries and educate users in order to lower override-to-reprogram ratios. The override-to-reprogram ratio is a principal indicator for library limit efficacy, and a downward trend has been observed at several IPI hospitals. Most other hospitals have experienced either a slow downward trend or some short-term increases and decreases but not much change over longer periods of time.

The basic comparative analysis (described above) serves as a coarse comparison mechanism. However, some hospitals want to compare data at multiple and deeper levels, so IPI offers a sophisticated “advanced” comparison area. In this area, users can select one or more hospitals and analyze alert data pertaining to specific care areas, drugs, infusion types, and limit libraries. For example, the user might select the “adult critical care” alert profile for a hospital and compare it with the profiles for four other hospitals; the user might then request data on alerts associated with infusions of vasopressin (a good example of a drug likely to be listed by different names and subject to different tall-man lettering standards across the five hospitals) to compare facility-specific alert totals, library limits, programmed values, and actions taken in response to alerts.

The IPI system not only offers shared data and powerful analytics but also supports collaborative decision-making and action, and it provides standardized templates to review outcomes. The IPI “narratives” feature is the single area that belongs to each hospital privately. The users within a hospital collaborate on actions and review outcomes together, but this information is not shared with other hospitals. The narrative allows a hospital to identify care areas, drugs, and other parameters for a given time period and access a spreadsheet presenting alert data for the selected variables. A standard template is used to catalog information in several categories (issues, discussion, limit library changes, education [nursing or pharmacy], and safety catches). The spreadsheets are created and shared online within the hospital; they can also be e-mailed and monitored by all members in the hospital’s IPI group. Narratives for each hospital are collected together in an IPI library, and hospitals can use the library of narratives for review and assessment so that changes can be connected to outcomes.

Outcomes associated with the system. The direct reduction of medication errors through the use of the IPI analytics tool is a work in progress; members of the IPI community hope to share data summarizing their progress in the near future. To date, the benefits and outcomes realized by IPI system end users have mainly related to greater efficiency of data analysis and reduc-
tion of alert fatigue. The Joint Commission identified improvement in the safety of clinical alarm systems as a 2014 National Patient Safety Goal (NPSG.06.01.01). IPI members are easily able to track alerts per device, which normalizes data between variously sized facilities. One user facility was able to quickly realize a 10% reduction in alerts per device (from 6.5 to 5.8). Another user noted a decrease in pump alerts (from greater than 1000 to less than 400) in a nine-month period, bolstering its efforts to meet NPSG.06.01.01, which is intended to improve the safety of clinical alarm systems. The ability to share intellectual content, including policies, procedures, and educational documents, greatly accelerates problem solving among members. For example, members have been able to standardize medication name clarification to prevent confusion between medications to be administered by intermittent versus continuous infusion.

Discussion

The use and value of medication safety groups that regularly review and analyze smart-pump data have been described, and most published literature regarding the analysis of smart-pump data has focused on individual facility processes. A recent collaboration between a community of hospitals and Purdue University has resulted in the creation of the IPI system, providing new opportunities to apply analytics tools and best practices through data sharing and collaboration.

The IPI system provides a members-only, secure, Web-based platform to upload smart-pump data. In addition to sharing a wide variety of analytics and investigative tools, representatives of the IPI member community meet and exchange information on a regular basis, providing opportunities for standardization of analytic methodology and drug libraries. The easy-to-use functionality for data analysis has been driven by IPI member input and has resulted in significant quality advancements and member satisfaction.

Conclusion

The formation of the IPI analytics system to support a community of hospitals has been successful in providing sophisticated tools for member facilities to review, investigate, and efficiently analyze smart-pump alert data, not only within a member facility but also across other member facilities, to further enhance smart pump library design.

References