Procedural Error Identification in Ward-based Drug Dispensing via RFID

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Abstract
Medication errors have long been identified as among the most common adverse events in health care, at the cost of both patient lives and scarce health resources. Many systems, manual and automated, have been developed to support health professionals in providing the ‘Five Rights’ of medication administration. But poor system design or implementation, the inherently stressful health care environment, and inadequate training often result in such systems being ignored or misused. Thus there has been increasing interest in systems that are ‘invisible’, ubiquitous, and context-aware. This paper describes the design and evaluation of a prototype smart drug tray, that uses RFID technology to support nurses in identifying patients and medications.

1. Introduction
In its landmark report, To Err is Human: Building a Safer Health System, the US Institute of Medicine (IOM) identify medication errors as one of the leading causes of death and injury in the US, and a sizable contributor to increasing health care costs [1]. In the years since, much attention has been paid to the ‘Five Rights’ of drug administration: Right patient, Right drug, Right dose, Right route, and Right time.
To date, attempts to reduce such errors have tended to be based on standardisation: standard drug labelling by drug manufacturers; computerised order entry by doctors; automated drug picking and unit dose packaging in the pharmacy; and at the bedside, drug administration checklists, and bar coded medication administration.
Medication errors, however, continue to occur and recent observational studies of drug administration, show that hospital staff routinely breach standard checklists and procedures, and shortcut or work around computerised systems intended to enforce such procedures [2, 3]. The inherently stressful nature of hospitals contributes to some breaches: staff under time pressure or with insufficient training may fall into habitual activity rather than follow new, unfamiliar procedures.
However some of the workarounds identified by Koppel et al [2] appear to be unavoidable consequence of poorly designed or implemented systems. Staff may be required to use equipment that is impractical for the hospital environment. Even when devices are suitable poorly designed software may “introduce a lot of overhead because [staff] must constantly log in and out of devices at hand, starting and stopping sets of applications, and browsing each to present the proper view for alternating activities” [4]. As a result there has been an increasing interest in technology that is ‘invisible’, ubiquitous, and context-aware. Radio Frequency Identification (RFID) is a promising technology in this area.

Section 2 of this paper reviews the literature on ward-based drug administration, the types and causes of medication errors, and how information systems generally and RFID specifically is being used to mitigate the causes. Section 3 describes the design of a prototype RFID-based system to address one common cause of medication errors. Section 4 describes how the prototype system has been evaluated to date, and the findings. Finally, section 5 presents conclusions and plans for further development.
2. Literature review

This section reviews the literature on ward-based drug administration, and the types and causes of medication errors. It describes how information systems generally are being used to mitigate the causes. Finally it reviews a sample of RFID-based systems for drug administration.

2.1. Ward-based drug administration errors

A good introduction to the ward-based drug administration process is given by Lane, Stanton & Harrison [5]. They perform a hierarchical task analysis (HTA), starting with four top-level tasks: 1) Check chart for medication details; 2) Acquire medication; 3) Administer drug to patient; and 4) Record dosage. Breaking each task down into its constituent activities the authors identify 86 activities at the lowest level. Many are near-duplicates, since they decompose the preparation and administration of different types of medication – tablets, liquids taken orally, infusions, and injections – separately. Lane et al go on to apply the systematic human error reduction and prediction approach (SHERPA) to their HTA. From this process they identify 79 potential errors.

Figure 1a shows how those 79 errors are spread across task. Figure 1b shows how they are divided across SHERPA’s types:

- **Action** errors indicate a failure in performing a manual action. An example is incorrectly programming an IV pump.
- **Checking** errors indicate a failure to confirm something. An example is failing to identify a patient.
- **Retrieval** errors indicate a failure in collecting information. An example is failing to read a medication label.
- **Selection** errors indicate a failure in selecting something. An example is selecting the wrong drug from the drug cart.

While the work of Lane et al identifies potential errors and the activities which are potentially most error-prone, the authors give no data on actual incidence. However, several researchers have attempted to do so. McDowell, Mt-Isa, Ashby & Ferner [6] performed a systematic review of previous studies on errors during the preparation and administration of IV medication. They identified nine studies published between 1995 and 2005, all involving European hospitals. Overall the studies suggest that about 73% of drug administrations included at least one error. The most significant were miscalculating the amount of diluent required to reconstitute powdered drugs, not administering the drug at the correct time, and not administering at the correct rate.

![Figure 1 - Potential errors during drug administration, by task and by type](image)
Similar results were reported by Westbrook et al [3] after observing nurses during medication rounds. Errors were divided into procedural (roughly corresponding to SHERPA’s retrieval and checking errors) and clinical (mainly action and selection errors). The authors found that around 74% of drug administrations included at least one procedural error, and that 25% included at least one clinical error. Of the clinical errors, the most common were drugs given at the wrong time (64%) and at the wrong rate (20%). The wrong volume of diluent was fourth on the list, at 8%, less significant than McDowell et al.

One clear difference in findings between the two studies is the number of medications given without first confirming the patient’s identity. Westbrook et al reported this as the most significant procedural error, occurring in almost 59% of administrations. Only two of the studies reviewed by McDowell et al specifically checked for failure to confirm patient identity, and both report no such errors occurred.

Westbrook et al’s separation of errors into procedural and clinical opens the way to consider whether there is a correlation between the two types. If a correlation does exist it would offer great promise for reducing clinical error. Such errors can generally only be detected retrospectively. For example, an observer watching a nurse would only be able to recognise a ‘wrong drug’ error if fully informed about the patient’s identity, medication chart, and which drug is about to be given. In contrast, procedural errors can often be detected prospectively. The same observer could notice a ‘giving medication without confirming patient identity’ error without having to know anything about the patient or the drug.

The initial results from Westbrook et al’s study didn’t suggest a correlation between procedural errors and clinical errors: 74% of administrations had the former, but only 25% the latter. However later work [7] does tend to support this and other studies have attempted to quantify the contribution of procedural errors to clinical errors. Hicks & Becker [8], analysing data on 74,000 medication errors entered into a US national incident reporting system from 2000 to 2004, report that about 28% are attributed to ‘procedure / protocol not followed’. Davis et al [9] identify failure to follow procedures and protocols as one of the ‘system factors’ that contribute to almost half the preventable adverse events in NZ hospitals. Thus there is some evidence that reducing procedural errors might be expected to reduce clinical errors.

2.2. Information systems solutions

Many types of information system have been proposed or developed with the objective of reducing procedural errors in drug administration. Table 1 shows a sample of such systems, grouped under the four high-level tasks identified by Lane et al.

CPOE systems require clinicians to enter medication orders into an electronic form, rather than hand writing orders on paper forms. The order entry process can ensure that all necessary information is entered, and passes ‘sanity checks’ for doses, drug interactions with existing medications, and similar. Electronic orders should be more easily retrievable than paper forms, and more legible than handwritten orders. The IoM favoured such systems in 2000, but later studies have raised questions over CPOE’s effectiveness, particularly in the early stages of their adoption [10].

Pharmacy robots are intended to reduce the scope for human error in selecting and preparing drugs. For example, the Robotic IV Automation (RIVA) system can automatically pick drugs and mix IV solutions [11], reducing the chance of incorrect diluents being used. ‘Porter’ robots can deliver drugs from the pharmacy to the wards [12].

BCMA systems automate or supplement the checks that nurses should make before administering medication. BCMA systems have been demonstrated to lower the incidence of medication errors [13], but barcodes present a number of usability challenges. For example, Koppel et al [2] note that thousands of patient scans and medication scans failed because the barcode labels were crinkled, smudged, chewed, torn, had liquid spilled on them, or were covered by other labels. Almost 100 patient scans failed because patients were asleep, breastfeeding, being bathed, or in some other position where the barcode was not visible without disturbing the patient. As a result nurses routinely scanned copies of patient identification barcodes kept on drug trolleys, on doors, on their belt rings, and other more convenient locations. In doing so, the likelihood of a patient being misidentified is clearly increased.

Although the term BCMA implies the use of barcodes, such systems can employ RFID instead. RFID technology operates on a similar principle. Tags encoding an ID number are attached to people or items, and then scanned by readers. The difference comes in how tags are scanned: barcodes are read optically, RFID tags and readers exchange wireless signals. This allows RFID tags to be read without a line of sight, and for multiple RFID tags to be read more quickly than a comparable number of barcodes. In comparisons of RFID- and barcode-based systems, RFID is generally found to be easier to use, though more expensive [14].
<table>
<thead>
<tr>
<th>Task</th>
<th>IS Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Check chart for medication details</td>
<td>Computerised physician order entry (CPOE)</td>
</tr>
<tr>
<td>Acquire medication</td>
<td>Pharmacy robots</td>
</tr>
<tr>
<td></td>
<td>Smart drug cabinets</td>
</tr>
<tr>
<td>Administer drug to patient</td>
<td>Schedulers</td>
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<tr>
<td></td>
<td>Barcode medication administration (BCMA)</td>
</tr>
<tr>
<td></td>
<td>‘Activity-based computing’ (ABC)</td>
</tr>
<tr>
<td>Record dosage</td>
<td>BCMA</td>
</tr>
</tbody>
</table>

2.3. Radio frequency identification in the hospital

In addition to BCMA systems, RFID has many applications within the hospital environment: identifying staff members and controlling access to restricted areas [15]; patient identification and medical record storage in military field hospitals [16]; drug identification and drug ‘pedigrees’ [17]; tracking wheelchairs, beds, IV pumps and other pieces of expensive medical equipment [18]; monitoring newborns [19] and patients with dementia [20]; and tracking the movement of staff and patients in busy areas, such as the surgical ward [21] and the Emergency Department (ED) [22].

RFID does, however, pose some risks in the hospital environment. Some RFID sensors have been demonstrated to affect pacemakers and other medical equipment [23, 24], although others haven’t [25, 26].

2.4. RFID in drug administration

RFID technology has been applied primarily to Lane et al’s ‘acquire medication’ and ‘administer medication’ phases. Smart drug cabinets [27] can automatically perform several ‘housekeeping’ tasks for tagged medications: keep real-time inventory, check whether drugs are past their expiry date, alert staff if drugs are stored incorrectly (eg – placed on shelves when they should be refrigerated). If nurses have an RFID-enabled badge or swipe-card, smart cabinets can automatically log who added or removed drugs. Swipe cards can also be used to control access to the restricted drugs, reducing the need for sets of keys.

Section 1 highlighted the prevalence of drugs being administered at the wrong time or omitted completely. Bravo et al [28] propose a system where nurses’ RFID-enabled mobile phones carry a schedule of drug administrations. Each nurse loads the schedule for his or her patients by touching the phone to an RFID tag on a large computer monitor that displays a summary for all patients. At the time for each scheduled administration, the phone sounds a reminder alarm. The nurse touches the phone to the patient’s RFID-enabled wristband, and then to another tag on the side of the bed to indicate that drugs have been given. At a change of shift the nurse going off duty literally ‘hands over’ by touching his or her phone to the phone of the nurse coming on.

The system proposed by Bravo et al uses a type of RFID known as Near Field Communication (NFC). As the name suggests, NFC only works over very short distances; in this case only when the phone is touching a tag. That largely nullifies RFID’s advantage in being able to read tags without a line of sight. Patients may, for instance, have to be woken in order for their tags to be read.

The touch-based interface does make Bravo et al’s proposed system very intuitive, and perhaps suits the ‘hands-on’ nature of nursing. However it also raises the risk of nosocomial infection. With the increasing use of handheld devices such as mobile phones and PDAs at the bedside, several studies have investigated the bacteria present on such devices. Most recently, Ulger et al [29] found that 95% of 200 mobile phones tested were contaminated with bacteria, including some known nosocomial pathogens. The authors also found that only 10% of staff that carried mobile phones made any effort to disinfect them.

Bar Code Medication Administration systems also require the nurse to use a handheld scanner, though rarely a mobile phone. BCMA systems typically use scanners attached to a ‘computer on wheels’ (COW), or built into a tablet computer or PDA. The scanners are typically kept several centimetres away from the patient’s wrist.
Lai et al [30] proposed an RFID-based BCMA system, using a PDA communicating with a laptop COW. The commercially available Intelliguard system [31] uses a COW with a handheld RFID reader to read the patient’s wristband and an RFID-enabled drug tray to read the tagged medications. Such systems would still be subject to some of the hardware and software related problems encountered by the nurses that Koppel et al observed: batteries failing, COWs being too unwieldy to navigate around patient beds, the software being slow or cumbersome, and the displays being too small or confusing.

An approach which avoids many of these problems is Activity Based Computing. Rather than requiring nurses to carry any type of reader or scanner, ABC embeds sensors and screens in the environment. An example is the ‘patient active zone’ (PAZ), proposed by Bardram [32]. An RFID built into a hospital bed constantly checks for tags in its zone. When the bed senses that only the patient (wearing an RFID wristband) is present, then a nearby monitor is available for him or her to watch TV or use the Internet. If the bed senses a nurse (wearing an RFID badge) enter the PAZ with a drug trolley (with an RFID tag attached) then the system infers that drug administration is about to happen and the screen automatically brings up the patient’s medication chart. The system indicates which medication container on the drug trolley is for this patient, and displays dose, route, and timing information.

The major challenge with ABC is, as Bardram points out, that inferring activity is inherently uncertain. For example, in the scenario described above the nurse may simply be passing through the patient’s PAZ en route to a different patient, or the nurse may be coming to see the patient for some reason other than drug administration.

3. Applying RFID to confirming patient identification

Westbrook et al [3] found failure to positively identify the patient as the most common procedural error in ward-based medication administration. This section describes a prototype system designed to work “invisibly” within an existing drug administration regime. “Invisibility” is one of the key facets of the vision of ubiquitous computing described by Weiser [33]. Rather than attempt to solve all the problems at once, a non-disruptive approach can allow particular features to be introduced as they are developed.

3.1. Design

An ABC approach may work for detecting high-level activities during drug administration: A nurse detected by the reader in the ‘drug supply activity zone’ is inferred to be acquiring medication. A nurse with a drug trolley detected by the reader in the ‘patient activity zone’ is inferred to be administering drugs. However, one sensor covering the entire bed, as in Bardram’s PAZ [32], is not well suited to distinguishing low-level activities, such as the nurse checking the patient’s wristband.

Detecting such a low-level activity will require the nurse to carry an RFID reader. Several obvious choices are suggested by the systems described in section 2.3. These include; a smart drug tray, similar to the smart drug cabinet; mobile phone, provided the RFID works beyond touch range; a reader connected to a PDA, a tablet computer, or a COW.

For an ‘invisible’ solution, the smart drug tray seems the preferable choice. It is a piece of equipment which nurses are accustomed to. It’s large enough to allow a reader to be embedded in it, and sturdy enough to provide the reader some protection.

The obvious disadvantage of the drug tray, in comparison to the other devices, is that it lacks input or output mechanisms. However, they may not be necessary. The primary objective for the device is to confirm that a patient wristband has been scanned, not to present the nurse with any data on the patient, nor ask the nurse to enter any data.

How might a smart drug tray be used to address the procedural error of failing to check a patient’s wristband to confirm his or her identity? A nurse would hold the tray near the patient to scan the patient’s RFID wristband. As each medication was removed from the tray, the reader would sense that and infer that it is being administered. If a medication was removed without a patient being identified, then an alarm would be raised.

It was decided to construct a prototype smart drug tray, in order to test the feasibility of these scenarios. First it had to be established that the device could avoid the two aspects of barcode reader operation that Koppel et al’s findings [2] clearly indicate caused the most problems for nurses: battery life and read rate.
3.2. Hardware

The smart drug tray would include an embedded RFID reader. For the prototype, a Tracient PadlR reader, operating in the Ultra High Frequency (UHF) range was selected. This reader has a number of features which are potentially useful for the prototype. Most importantly, it emits very little electromagnetic energy. In previous testing, this reader created no interference with other electronic medical devices known to be sensitive to such interference, even at full power [26]. That testing was performed in an operating room, and there may be common ward devices that are more susceptible. If so, the reader’s power level is adjustable and can be further reduced. The reader is battery-powered, so does not need to be tethered to a COW. It can also be configured to check for RFID tags continuously at a fixed interval, or to check only when a button is pressed. This latter mode allows battery power to be conserved.

LED indicators and a speaker are built into the reader. These can provide visual and/or audio cues to nurses to, for example, confirm a successful read. The reader has on-board memory to store details for up to 900 reads. It is also equipped with Bluetooth, so details of each read can be sent immediately to a computer if required. For example, if the nurse was being observed, the reader could send details of each tag read to a PDA being carried by the observer.

3.3. Software

Two simple pieces of software were developed. The first, dubbed Configure, allowed the features mentioned above to be configured into a profile. For example, to be truly invisible the reader would need to be interrogating for tags continuously (so the nurse need not press any buttons), at a reasonably long range. But there may be scenarios where a shorter range is preferred or push-button reading is required. Profiles could be created to enforce a standard way of using the reader. Or, to permit greater invisibility, profiles might be set up for each nurse, to suit his or her individual activity patterns.

The second piece of software, called Monitor, forms a Bluetooth connection with the reader and displays the details of each tag read. The standard data for each read is date, time, and tag ID. The tag ID can be resolved to a patient, medication, or ‘unknown’. Optionally, any other data stored on the tag can also be displayed. The data can be saved to a file if required.

4. Evaluation

This section describes how the prototype’s battery life and read rate were evaluated, and the results. Given the potential for use in sensing medications on the tray, the prototype’s read rate was tested for both patient wristbands and tagged medications.

4.1. Battery life

Tracient suggest that the reader is capable of 15,000 reads on a full battery charge [34]. If reading continuously, once per second, that allows for an operating time between charges of just over four hours. To test this, the reader was fully charged and set to read continuously, once per second. To simulate the maximum battery drain, the reader was also set to beep on each successful read and to transmit the data from each read to a PC over a Bluetooth connection. This test was repeated five times. The minimum number of reads was 17,306, allowing an operating time of almost five hours. The average over five runs was 22,777, allowing approximately 6 hours, 20 minutes operating time. If push-button reading were used, the operating time could run to many days.

4.2. Read rate – patient wristband

The reader was attached to the inside edge of a tray, as shown in Figure 2. The tray measures 23cm wide, 32cm long, and 39cm on the diagonal. A person acting as a patient wore a wristband with an Alien passive UHF RFID tag attached. This tag was selected based on the authors’ previous experience, as offering a good balance between small size and long read range.

The reader was initially set to full power (27 dBm) and placed 10cm away from the wristband, as shown in Figure 3. This is intended to represent a typical reading position, with the patient’s arm resting flat on the bed at his or her side. The bottom of the tray is approximately level with the top of the patient’s wrist.
Table 2 – Wristband read rates by range and power level

<table>
<thead>
<tr>
<th>Power level (dBm)</th>
<th>Read rate % at...</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>10cm</td>
</tr>
<tr>
<td>27</td>
<td>100</td>
</tr>
<tr>
<td>25</td>
<td>100</td>
</tr>
<tr>
<td>22.5</td>
<td>100</td>
</tr>
<tr>
<td>20</td>
<td>100</td>
</tr>
</tbody>
</table>

The reader was allowed to read 50 times, and the read rate calculated as the number of successful reads / 50. If the read rate was reliable – deemed 80% or higher - then the reader was moved another 10cm away. The test was repeated at each of the power levels 25 dBm, 22.5 dBm, and 20 dBm. The results are summarised in Table 2.

At full power the patient’s wristband could be read reliably at a distance of over 60 cm. As expected, the range at which a reliable read rate was possible dropped as power level was decreased. However, even at relatively low power of 20 dBm, the wristband could be read reliably at a distance of over 20 cm.

Larger tags were tested. The longest read range was 75cm, for a UPM Raflatac tag. However that was approximately 50% larger than the Alien tag, which may be too unwieldy for a patient wristband or medication container.

4.3. Read rate – medications

Four items were selected to represent various types of medication containers: two pill bottles of different sizes, a bottle of liquid, and a syringe. The items were tagged with the same type of Alien RFID tag used in the patient wristband.

First the four items were placed as shown in Figure 4, one in each corner of the tray. This represents the extreme case of the drugs being spread out across the tray.

The reader was initially set to full power (27 dBm), allowed to read 50 times, and the read rate calculated. The test was repeated at each of the power levels 25 dBm, 22.5 dBm, and 20 dBm.
Table 3 - Tagged medication read rates by position and power level

<table>
<thead>
<tr>
<th>Power level (dBm)</th>
<th>Read rate % at corners</th>
<th>Read rate % in centre</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tag 1</td>
<td>Tag 2</td>
</tr>
<tr>
<td>27</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>25</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>22.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Then the items were then placed together in the centre of the tray, as shown in Figure 5. This is a more likely scenario. The same sequence of tests was repeated. The results are shown in Table 3.

Interestingly, when the medication containers were spread out, the corner furthest from the reader’s antenna appeared to be read most reliably. The reader clearly has ‘blind spots’ when it comes to detecting medications in the other corners. Tag 1 was never read when placed in the corner. Tags 2 and 3 were only read reliably in the corners when the tag was operating at 25 dBm or greater power. When the medication containers were clustered together, tags 1, 2, and 3 were read more reliably overall, but reading tag 4 was slightly less reliable.

5. Further development and conclusion

To date, the prototype has been demonstrated to the Principal Pharmacist for Medication Safety at a large city hospital. His feedback was positive, and has encouraged plans for further development. A system intended to be as ‘invisible’ as the RFID-enabled drug tray obviously requires a great deal more evaluation in the hospital environment by the nurses who will use it every day.

Short term plans include greater integration of the drug tray and reader. In particular the casing of the reader will be removed, and the internal components embedded in the tray. The corners of the drug tray may also be modified to reduce the size of the blind spots evident in the medication read rate testing.

Testing of other RFID tags is also planned, to identify the optimum balance of long read range and small size. Larger tags are preferable to give greater range, but are more awkward to attach to medication containers and to embed in patient wristbands. More extensive testing for possible electromagnetic interference with electronic medical devices common in the ward will also be necessary.
In the longer term, additional software is envisaged that would allow detection of other procedural errors. Tagged medications and a database of patient medication orders would permit the RFID-enabled drug tray to check, for example, for nurses preparing medication for more than one patient at a time. The flexible configuration options available in the reader also prompt some intriguing experiment ideas. For instance, does a tool that actively encourages adherence to procedures (say, requires short range, push-button reading of patient wristbands) result in greater adherence than a tool that passively encourages adherence (allows longer-range, continuous reading)?

The IoM recently renewed its call for medication errors to be made a priority in patient safety improvement programmes [35]. Notwithstanding the progress made in recent years, there is clearly still great interest in further improvement. The link between procedural errors and clinical errors in ward-based medication administration represents a promising avenue for further research. RFID technology offers great potential for developing ‘invisible’, ubiquitous, context aware systems that will support that work. The prototype RFID-enabled drug tray described in this paper is another step towards developing such systems.

6. References


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