

Procedural Error Identification in Ward-based Drug Dispensing via RFID

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Abstract

Drug 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 drug 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 drug 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.

Drug 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 consequences 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 drug 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 drug errors. Section 4 describes laboratory evaluation of the prototype system. 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 drug 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

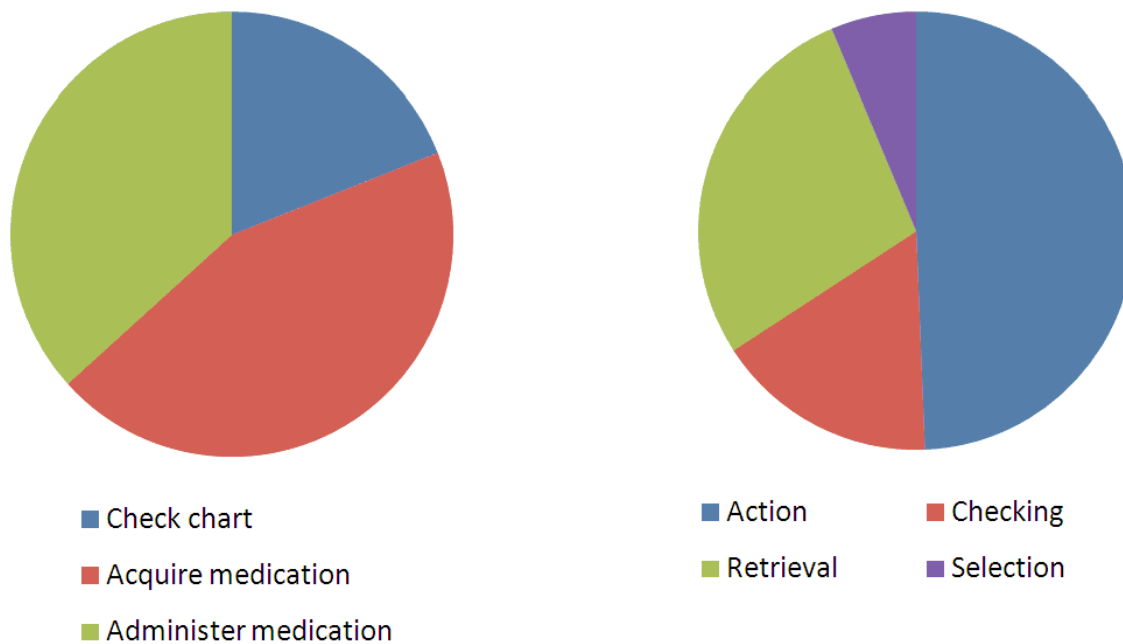
A good introduction to the ward-based drug administration process is given by Lane, Stanton & Harrison [5]. They perform a hierarchical task analysis (HTA), starting with four top-level tasks: 1) Check chart for medication details; 2) Acquire medication; 3) Administer drug to patient; and 4) Record dosage. Breaking each task down into its constituent activities the authors identify 86 activities at the lowest level. Many are near-duplicates, since the preparation and administration of different types of drugs – tablets, liquids taken orally, infusions, and injections – are decomposed separately. A Systematic Human Error Reduction and Prediction Approach (SHERPA) is then applied to identify potential errors. The authors identify 79 potential errors across the 86 activities.

Figure 1a shows how those 79 errors are divided amongst the top-level tasks noted above (none are associated with Record dosage). Figure 1b shows how they are divided across SHERPA's four error types:

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

While the work of Lane et al identifies possible 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 drugs. 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 common 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.

Similar results were reported by Westbrook et al [3] after observing nurses during ward medication rounds. Errors were divided into two types: 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 one or more procedural errors, 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 common than McDowell et al.



(a) Proportion of errors by task

(b) Proportion of error types

Figure 1 - Potential errors during drug administration, by task and by type [5]

The most common procedural error reported by Westbrook et al was the failure to confirm a patient's identity before administering drugs, occurring in almost 59% of administrations. In contrast, only two of the studies reviewed by McDowell et al specifically checked for failure to confirm patient identity, and both reported no such errors occurred.

Several causes of drug errors are widely acknowledged. McDowell et al state that: "Factors such as fatigue, inexperience, and haste are known generally to increase error rates" [6, pg 344]. Those authors go on to identify another possible cause: "However, that would still leave open the question of whether the chance of an error at some later stage were dependent on the occurrence of an error at an earlier stage" [6, pg 344]. Westbrook et al's separation of errors into procedural and clinical offers another way to phrase the question: Is there a correlation between procedural errors and clinical errors?

If such a correlation does exist it would offer great promise for reducing clinical error. Clinical errors can generally only be detected retrospectively. An observer watching a nurse would only be able to detect a 'wrong drug' error, for instance, if fully informed about the patient's identity, expected medications, and which medication 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 medications. Recent studies of BCMA systems suggest they do lower the incidence of drug errors [13], but barcodes have a number of shortcomings. For example, Koppel et al [2], reporting on two BCMA implementations, note that thousands of patient scans and drug 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 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 are clearly increased.

Table 1 – IS solutions for reducing errors during drug administration tasks

Task	IS Solutions
Check chart for medication details	Computerised physician order entry (CPOE) Drug interaction databases
Acquire medication	Pharmacy robots Smart drug cabinets
Administer drug to patient	Medication reminder alarms Barcode medication administration (BCMA) 'Activity-based computing' (ABC)
Record dosage	BCMA

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. RFID tags have no markings to be defaced or obscured. RFID tags can be read without a line of sight. Each RFID tag, in principle, has a unique ID number, making it possible to distinguish the tag worn by a patient from any 'copies' in more convenient places. In comparisons of RFID- and barcode-based systems, RFID is generally found to be easier to use, though more expensive [14].

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 newborn [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 keep real-time inventory of tagged drugs, check whether drugs are past their expiry date, and 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 adds or removes 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 relevant time, 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.

BCMA 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 (ABC). 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 reader 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 drugs on the drug trolley are for this patient, and displays dose, route, and timing information.

The major challenge for 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 drug administration. This section describes the design of a prototype RFID-based system, informed by the strengths and weaknesses of the systems described in section 2.4, to address that error.

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 medication. 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 would require the nurse to carry an RFID reader. Several obvious choices are suggested by the systems already described. These include: mobile phone, provided the RFID works beyond touch range; a reader connected to a PDA, a tablet computer, or a COW; or a smart drug tray, similar to the smart drug cabinet, but holding only one patient's medication at a time.

To minimise the overhead for nurses, 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 before any drugs are given, not to present the nurse with any data on the patient, nor ask the nurse to enter any data.

A smart drug tray would be able to read tags on any drug containers placed on tray, and any tags on people or objects near the tray. How might such a device infer the activities involved in drug administration from the presence or absence of tags?

1. An RFID tag is placed on the work surface in the drug supply room. The nurse puts the drug tray down on or near the tag. If the tray is empty, the system can infer that nurse is preparing medications. (If the tray contains drug containers, the system can infer that the nurse is returning from giving medications.)
2. When the work surface tag is no longer detected, the system can infer that the nurse is leaving the drug supply room. It takes a snapshot of the drug containers currently on the tray.
3. If a drug container tag is no longer detected, the system can infer that the nurse has removed it from the tray and is administering the drug to a patient.
4. If no patient tag has been detected between steps 2 and 3, the system can infer that the patient's identity has not been confirmed.

The first stage in creating the smart drug tray was to identify suitable RFID hardware.

3.2. Hardware

In order to give the smart drug tray a reasonable read range, RFID equipment operating in the Ultra High Frequency (UHF) range seemed most suitable. The Tracient Padl-R UHF reader was selected, as it has a number of other potentially useful features. Most importantly, the reader 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]. If such interference were encountered, the reader's power output can be reduced. The reader is battery-powered and has Bluetooth for wireless communication, so does not need to be tethered to a COW. LED indicators and a speaker are built into the reader, providing options for visual and/or audio feedback to nurses. Finally, the reader can be set to read continuously at regular intervals, or to perform single reads at the touch of a button.

Setting up these features in different configurations allows for a number of distinct approaches to using the smart drug tray. For example:

- ‘Confirm’ configuration: push-button reads so that the nurse must manually trigger reads, low power so that the nurse must be close to the patient, visual or audio cue to confirm a successful read of the patient wristband
- ‘Warn’ configuration: continuous reads so that the nurse needn’t manually trigger reads, high power, visual or audio cue to warn only if the patient wristband has not been read

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.

3.3. Software

Two simple pieces of software were developed. The first, dubbed Configure, allowed the features mentioned above to be configured. Configurations could be set at an institutional level to enforce actions, or for each nurse to suit his or her individual work style.

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, a 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 laboratory evaluation of the prototype smart drug tray. Based on the BCMA usability issues highlighted by Koppel et al [2], three aspects of performance were of particular interest: battery life; read reliability for patient wristbands; and read reliability for drug containers.

4.1. Battery Life

Tracient suggest that the reader is capable of 15,000 reads on a full battery charge [33]. 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 create 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 for 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 Reliability – Patient Wristband

A person acting as a patient wore a wristband with an Alien passive UHF RFID tag attached. This tag was selected based on previous experience, as offering a good balance between size and read range.

One set of tests was performed to find the distance at which tags could be read reliably at different reader power levels. The reader was initially set to full power (27 dBm) and placed 10cm away from the wristband. As shown in Figure 3 the tag was on the outside of the patient’s wrist, directly facing the reader. The reader was allowed to read 100 times, and the number of *successful* reads counted. If there were 80 or more 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 tags could be reliably read 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.

A second set of tests was performed to observe the effect of obscuring tags. The reader was reset to full power, and placed 10 cm away from the wristband. The wristband was covered with a woollen blanket, and the number of successful reads out of 100 counted. If there were 80 or more then the reader was moved another 10cm away. The test was repeated, first with the tag slightly obscured by the patient’s body (on top of the wrist), with the tag mostly



Figure 2 - Reader in tray



Figure 3 - Reading patient wristband

Table 2 – Wristband read reliability by range and power level (tag on outside of wrist)

Power level (dBm)	Successful reads out of 100 at distance ...						
	10cm	20cm	30cm	40cm	50cm	60cm	70cm
27	100	100	100	100	100	88	0
25	100	100	100	100	100	0	-
22.5	100	100	86	60	-	-	-
20	100	100	66	-	-	-	-

Table 3 - Wristband read reliability by tag position / state (reader at full power)

Tag obscured	Successful reads out of 100 at distance ...						
	10cm	20cm	30cm	40cm	50cm	60cm	70cm
Fully - covered by blanket	100	100	100	96	84	0	-
Slightly – top of wrist	100	100	100	100	100	0	-
Mostly – inside of wrist	100	0	-	-	-	-	-
Fully - bottom of wrist	0	-	-	-	-	-	-

obscured (on the inside of the patient’s wrist) and with the tag fully obscured (on the bottom of the patient’s wrist). The results are summarised in Table 3.

Even though the blanket fully obscured the tag, as a relatively thin cover it only reduced the distance at which tags could be read reliably by 10 cm. The same result was observed when tags were partially obscured by the patient’s wrist. This was expected, as the human body absorbs the electromagnetic energy in RFID signals, reducing their range. That is clearly evident in the results seen when the tag was fully obscured.

4.3. Read Reliability – Drug Containers

Seven items, shown in Figure 4, were selected to represent various types of drug containers: two plastic pill bottles of different sizes, a plastic bottle of liquid, a glass bottle of liquid, a syringe, a blister pack of pills, and a tube of gel. The items were tagged with the same type of Alien RFID tag used on the patient wristband.

Two sets of tests were performed to observe how reliably the containers could be read at different reader power levels. The four plastic containers were first placed together in the centre of the tray, as shown in Figure 5. The reader was initially set to full power (27 dBm), allowed to read 100 times, and the number of successful reads of *each tag* counted. The test was repeated at each of the power levels 25 dBm, 22.5 dBm, and 20 dBm. To see if there were any ‘blind spots’ on the tray, the test was repeated with one container in each corner of the tray as shown in Figure 6. The results from both sets of tests are shown in Table 4 - Drug container read reliability for four containers, by position and power level.

Interestingly, when the 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 containers 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



Figure 4- Tagged drug containers



Figure 5 - Drug containers in centre of tray

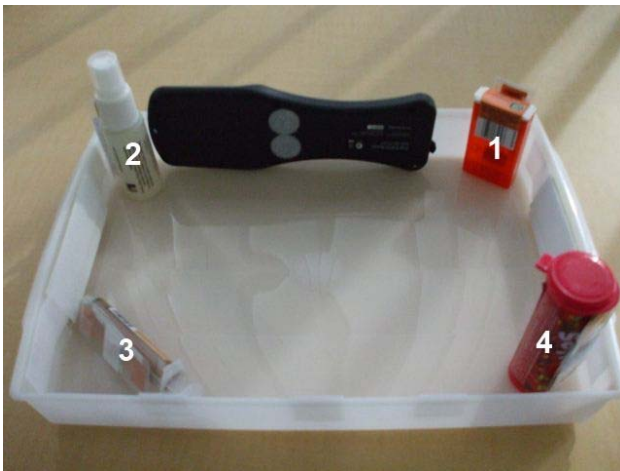


Figure 6 – Drug containers in corners of tray

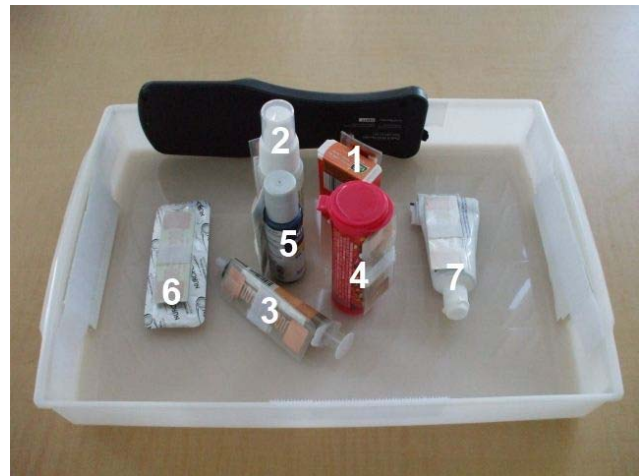


Figure 7 - Drug containers in centre of tray

Table 4 - Drug container read reliability for four containers, by position and power level

Power level (dBm)	Successful reads out of 100 in centre				Successful reads out of 100 in corners			
	Tag 1	Tag 2	Tag 3	Tag 4	Tag 1	Tag 2	Tag 3	Tag 4
27	100	100	100	100	0	100	100	100
25	100	100	100	100	0	100	70	100
22.5	0	90	90	80	0	0	0	100
20	0	80	100	70	0	0	0	90

Table 5 - Drug container read reliability by number of containers

# of containers	Successful reads out of 100 in centre						
	Tag 1	Tag 2	Tag 3	Tag 4	Tag 5	Tag 6	Tag 7
5	100	100	100	100	99	-	-
6	100	100	99	49	18	0	-
7	100	99	97	46	15	0	0

25 dBm or greater power. When the containers were clustered together, tags 1, 2, and 3 were read more reliably overall, but reading tag 4 was slightly less reliable.

A third set of tests was performed to observe the effect of adding further containers to the tray. The reader was reset to full power, and the initial four containers returned to their position in the centre of the tray. The remaining containers were added one at a time, as shown by the numbering in Figure 7. After each addition the reader was allowed to read 100 times and the number of successful reads of each tag counted. The results are shown in Table 5.

Adding the glass bottle of liquid appeared to have no effect. However, adding the blister pack of pills caused the glass bottle and the syringe to be read much less reliably. The blister pack itself was not read at all. This is likely due to the blister pack's aluminium foil covering. Metal is capable of reflecting and refracting the wireless signals used by RFID readers, rendering them less effective. Another possible explanation is tag collision. With several RFID tags close together, the signals they send to the reader can interfere with each other, resulting in fewer successful reads. But tag collision seems unlikely to have affected tags 4 and 5 without also affecting at least tag 3. Tag collision is, however, a feasible explanation for the tube not being read at all when it was added.

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 smart drug tray will require extensive evaluation in the hospital environment by the nurses who will use it every day.

To prepare the smart drug tray for such user evaluation, several improvements are necessary. While the reader performed well at reading patient wristbands, nurses would currently have to hold the tray with the reader side facing the patient. The tray should have a second RFID reader on the opposite side, so that the nurse isn't required to hold it in a certain way. A second reader should also remove the blind spot, and mitigate the effect of tag collision.

To make the RFID hardware more invisible the internal components of the RFID readers should be physically embedded in the tray. This raises questions about the most suitable way to use the visual and audio feedback options available. Audio feedback seems more sensible; nurses won't be constantly looking at the tray, so may miss LED changes. But is the reader's audio feedback distinguishable from the myriad other electronic noises made in the ward environment?

Testing of other RFID tags is also planned. In particular, RFID tags designed for use on metal items are available, and may reduce the impact of aluminium foil common in certain drug packaging. Further investigation into the optimum balance of tag size and read range is also required. Larger tags are preferable to give greater range, but are more awkward to attach to medication containers and to embed in patient wristbands.

In the longer term, a smart drug tray should allow detection of other procedural errors. Access to a database of patient medication orders would permit the RFID-enabled drug tray to check, for example, whether the nurse has the correct medication for the identified patient, and is giving it at the right time.. The flexible configuration options available in the reader also prompt some intriguing experiment ideas. For instance, does smart drug tray that actively encourages adherence to procedures (say, by using the Confirm configuration suggested in section 3.2) result in greater adherence than a tool that passively encourages adherence (by using the Warn configuration)?

The IoM recently renewed its call for medication errors to be made a priority in patient safety improvement programmes [34]. 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.

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