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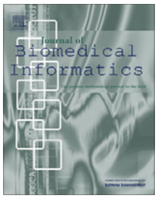

Introducing RFID technology in dynamic and time-critical medical settings: Requirements and challenges

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ABSTRACT

We describe the process of introducing RFID technology in the trauma bay of a trauma center to support fast-paced and complex teamwork during resuscitation. We analyzed trauma resuscitation tasks, photographs of medical tools, and videos of simulated resuscitations to gain insight into resuscitation tasks, work practices and procedures. Based on these data, we discuss strategies for placing RFID tags on medical tools and for placing antennas in the environment for optimal tracking and activity recognition. Results from our preliminary RFID deployment in the trauma bay show the feasibility of our approach for tracking tools and for recognizing trauma team activities. We conclude by discussing implications for and challenges to introducing RFID technology in other similar settings characterized by dynamic and collocated collaboration.

1. Introduction

Recent technological advances in the areas of activity, voice, gesture and emotion detection and recognition have opened up new avenues for improving safety and quality of patient care. Among these, radio-frequency identification (RFID) technology is most promising given its unobtrusiveness and relatively easy integration into the healthcare systems. RFID technology also offers several advantages over the existing identification systems. Compared to the widely used barcode system, RFID does not require focused passing of objects over scanners, which minimizes human intervention and interference with task performance. It also enables faster and simultaneous scanning of multiple items, longer read range, and does not require line-of-sight (i.e., radio signal is detectable without direct visibility) [1]. RFID technology is currently used for patient and medical personnel tracking [2,3], resources tracking for rapid use of medical devices [4], and medications tracking for preventing errors and counterfeiting [5]. Although the total cost of adopting RFID in healthcare is still significant, the cost of RFID tags and antennas has been decreasing over the past several years, opening opportunities for broader application [6].

Despite its growing use in healthcare [3,7], RFID technology has not yet been evaluated in time- and safety–critical medical settings, such as trauma resuscitation. The fast-paced, high-risk environment of trauma resuscitation is a challenging domain for introducing RFID technology for several reasons. First, resuscitation rooms are crowded, with many people moving around, causing interference for radio signals. Second, the number of objects—medical tools, supplies and equipment—that needs to be tagged is on the order of 50, requiring many RFID tags, which in turn reduces detecting capacity of tag readers due to longer read cycles and higher probability of collisions. Third, while in use, RFID tags may be covered by providers' hands, which blocks radio signals from tags. Fourth, medical tools are made of different materials and some supplies contain fluids, which may have adverse effects on the radio signal. Finally, some objects come in plastic wrapping and can be tagged only externally; once the wrapping is removed, tracking of the object stops. Initial attempts to deploy information systems to aid trauma teams have been promising, but have shown limited usability [8–10]. The lack of success is due to the challenges of manually entering data from diverse sources in a dynamic environment, the difficulty of synthesizing output and recommendations, and resistance to technology that offered no major improvement.

Our long-term research goal is to develop a context-aware system to provide computerized support for real-time decision making during fast-paced and complex medical events. We envision such system as a combination of different approaches and

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technologies—RFID, digital pen technology, computer vision, and other sensors—that will aid in capturing critical patient information from the environment and be used at different levels of activity recognition to support real-time decision making. For example, information collected and synthesized for a task such as patient intubation could provide feedback to decision makers about the exact timing of the intervention, the time it took to intervene, and if the intervention was done correctly. Alternatively, the system could track the use of different instruments during patient care and provide real-time information about the start and completion of particular tasks (e.g., use of thermometer indicates measurement of patient temperature).

In this paper, we use trauma resuscitation as an example domain and describe the process of deriving design requirements for one component of our future context-aware system, namely, the system for tracking trauma team activities using minimally intrusive RFID technology. Although we recognize the benefits of using several types of sensors simultaneously (accuracy of detecting and recognizing an activity increases with simultaneous use of several technologies), we chose an incremental design approach by which we study system components in isolation to gain the necessary knowledge about design requirements for each component. This incremental approach is also helpful in learning about the effectiveness of individual technologies in capturing, tracking or detecting team activities. To derive design requirements for our RFID system component, we performed an analysis of team activities during simulation in a level 1 (highest) trauma center over the course of 2 years.

The goals of the current research were threefold. First, we studied domain tasks and procedures to identify activities and objects that require tracking. Second, we used the results from tasks and procedures analysis, and from laboratory experiments to find the optimal placement for RFID antennas and tags in the environment. Third, we developed guidelines for interpreting radio signals from tagged objects, i.e., whether an object is stationary, carried from one place to another, or in use. To deduce team activities based on radio signals, we analyzed work practices and providers' interactions with objects. Our description of the requirements gathering process and preliminary results from RFID technology deployment offer valuable insight into challenges to introducing RFID technology in dynamic work environments.

The contributions of this paper are:

- Identification of tasks and objects that require tracking for real-time support of decision making during fast-paced and complex medical activities, such as trauma resuscitation.
- Strategies for placing RFID tags and antennas in the environment for optimal tracking and activity recognition.
- Guidelines for interpreting radio signals from tagged objects for accurate task detection.
- Initial results from the system deployment at a trauma center during simulated resuscitations with trauma team members.
- Challenges to introducing RFID technology in time- and safety critical medical settings.

1.1. Context-aware systems and RFID technology in dynamic work settings

Prior research on context-aware systems has shown feasibility of using sensors for studying complex activities in dynamic work environments [5,11–21]. To detect and track objects or people, these systems have used different types of sensing technologies and approaches, including computer vision, accelerometers, ultra wide band (UWB) sensors, active RFID tags, passive RFID tags, keyword spotting and digital pen technology. Context-aware systems have the potential to support work of interdisciplinary medical teams in fast-paced and unpredictable medical domains, where context refers to the currently performed activity.

Trauma resuscitation tasks are dynamic activities and consist of many body movements (e.g., walking, bending down, raising arms, moving fingers) and manipulations (e.g., interactions with objects and patients). While simple activities, such as walking or raising arms can be recognized by body motion sensing through computer vision or body sensor networks [22], complex activities require high-level cues, including spoken words, body location, or objects in use [23]. Vankipuram et al. [13] and Kannampallil et al. [14] used active RFID tags to deduce coarse-grained activities of clinicians in a trauma unit, including their location and movement. Our research extends this prior work by exploring the use of passive RFID tags for detecting and interpreting finer-grained tasks, such as those performed on patients. We focus on analyzing the use of medical objects and tools rather than clinicians' location and movement patterns. Because objects are uniquely associated with different tasks, they can serve as reliable indicators for current tasks and team activities. For example, the use of manual blood pressure (BP) cuff implies that blood pressure is being measured.

High-level cues such as spoken words and objects in use have already been applied for tracking medical activities, including drip injection tasks [24], classification of surgery phases [12], and maintaining situation awareness during surgery [16]. To detect such activities, researchers have used wearable RFID readers or barcodes. Although these near-field technologies yield high accuracy in interaction detection, they require that providers remember to attach readers to their gowns or body parts—a requirement that may be highly intrusive in critical-care settings. Because our plan is to evaluate the feasibility of our approach through continuous experiments in the actual setting of the trauma bay, we needed to ensure that the placement of RFID tags and readers is minimally disruptive to team members' activities. To accomplish this goal, we used passive RFID technology.

1.1.1. Passive RFID: Advantages and disadvantages

Compared to active RFID tags and other sensing technologies, passive RFID technology offers several advantages, making it a suitable solution for highly dynamic and crowded medical settings. First, passive tags do not require special maintenance because they have their own energy source and operate without batteries; they receive energy from RFID readers and then use this energy to send signals back to the reader. Second, passive RFID tags are smaller, which makes them convenient for attaching to small medical objects and usable at the item level. They can also be used for disposable items such as intravenous catheters and tubes; using motion sensors or active RFID tags for disposable items is not feasible. Third, RFID data contains little or no personal information, making this technology an ideal solution for capturing information in medical settings. Although computer vision offers most of these advantages, its use is limited by privacy concerns as cameras provide a permanent visual record of people and their activities. Finally, passive RFID tags are cheaper compared to other tracking technologies, which is an important factor if the amount of objects that need tagging exceeds 100. Accurate detection of objects during resuscitation events often requires tagging more than 100 objects per resuscitation, showing the feasibility of using passive RFID tags.

Despite these advantages, long-range passive RFID technology has received limited attention in activity recognition community due to its performance limitations. Compared to active sensors with read range up to tens of meters, passive RFID tags have a much shorter read range, up to 4 m. Although a significant disadvantage for a hospital-wide tracking applications, this limitation does not affect activity recognition systems that are intended for contained and relatively small environments such as the trauma bay. In addition, detection rates significantly degrade when passive RFID tags are attached to objects made of metal or filed with liquid. Our laboratory experiments and real-world deployment have shown that careful placement of RFID tags along the object edges and using special on-metal tags may help overcome this limitation. Finally, a passive RFID system requires highly powered readers to enable powering up the tags. Although prior research has shown that the high power emitted by readers may cause malfunctioning of medical devices [25], we did not encounter this problem during the deployment of our system in the actual trauma bay.

In sections that follow, we first provide an overview of the trauma resuscitation domain and tools and equipment used during patient evaluation. We then describe our study and methods, followed by a summary of findings from the analysis of team activities and from the RFID tracking system deployment at our research site. We conclude by discussing implications for and challenges to introducing RFID technology in dynamic work settings.

2. Trauma resuscitation domain

Trauma resuscitation—the fast-paced and dynamic process of treating severely injured patients immediately after injury—takes place in the trauma bay, a designated room in the emergency department (ED). Resuscitations usually last between 20 and 30 min and require specialists from several medical disciplines, including emergency medicine, surgery, anesthesia, critical care and nursing. Each trauma team member has a clearly defined role with an associated set of responsibilities so that tasks can be performed efficiently [26]. The size and composition of the team varies depending on the individual hospital and the anticipated severity of patient injury. At most academic medical centers, teams typically consist of a senior surgical resident or fellow (team leader), an attending surgeon, a junior surgical resident (physician doer), an anesthesiologist, a respiratory therapist, a technician, and nurses.

To limit the impact of human factors in this safety–critical domain, trauma teams follow a standard protocol, Advanced Trauma Life Support (ATLS), which defines the sequence of evaluation and treatment steps [26]. The protocol starts with the airway assessment (Airway [A]), and is followed by the assessment of respiratory dynamics (Breathing [B]), hemodynamic status (Circulation [C]) and neurological state (Disability [D]). This initial evaluation of major physiological systems (primary survey) is then followed by a detailed examination for other injuries (secondary survey). The evaluation process is repeated iteratively to uncover potential changes in patient status and to monitor the effects of treatments.

2.1. An ecology of trauma resuscitation equipment

Trauma team members rely on a range of specially designed instruments and equipment to conduct patient evaluation and administer treatments during resuscitation events. While the use of instruments in other medical settings varies (e.g., instruments needed for surgical procedures vary case-by-case [27]), instruments in trauma resuscitation are relatively constant. Typical tools and equipment found in the resuscitation bay of a trauma center includes the following items.

2.1.1. Airway management and ventilation equipment

Most airway-related equipment is located near the head of the patient bed to allow for an easy reach during airway management. Basic airway equipment includes intubation instruments such as laryngoscope handle and blades and endotracheal (ET) tubes for establishing an airway; nasogastric/orogastric tubes for gastric decompression; cervical collars for neck immobilization; bag valve masks (BVMs) and oxygen masks for ventilation; suction equipment for clearing the airway from obstructions; and, a ventilator.

2.1.2. Vital signs monitor and related equipment

The vital signs monitor is positioned next to the patient bed and displays the patient's blood pressure (BP), ECG waveforms, heart rate or pulse, oxygen saturation and respiratory rate. To connect the patient to the monitor, a technician places ECG leads, automatic BP cuff, pulse oximeter, and end-tidal CO_2 monitor on the patient. These activities are performed during the first few minutes after patient arrival. When the patient is stabilized and readied for transfer to another hospital unit, a switch is made from the fixed vital signs monitor to a portable monitor. Other monitoring equipment includes a thermometer, CO_2 detector for verifying CO_2 exhalation upon intubation, an otoscope and ophthalmoscope for assessing the ears and eyes, respectively, and Foley (bladder) catheters for monitoring urinary output.

2.1.3. Vascular access equipment and supplies

Access to the vascular system is obtained by the insertion of intravenous catheters. These catheters are used for administration of medications, fluid and blood products. Items used for intravenous access are initially packed together in an IV toolkit and include a catheter of the appropriate size, alcohol swabs, adhesive tape, adhesive dressing, and gauze.

2.1.4. Chest tube and equipment for drainage of the pleural cavity

Patients with chest injuries may need a tube in their chest to drain air or blood from the pleural space. Systems for drainage of the chest provide suction, record the pressure of the pleural space, and collect fluid. Equipment for inserting the chest tube is typically placed along the walls in the trauma bay.

2.1.5. Temperature control

Several tools can be used to control the patient's temperature, including a blood warmer device, a hollow blanket that blows warm air, and warm blankets.

2.1.6. Diagnostic and imaging equipment

The trauma bay is also equipped with devices to analyze hemoglobin and glucose levels in blood. Other tools include an ultrasound device for diagnosing intra-abdominal or thoracic fluid. The X-ray machine is either located outside the trauma bay with a fixed installation or brought into the room as needed. After taking an X-ray image, the technician carries the cassettes to the radiology department where images are processed. Cassettes are read electronically and imaging information is brought up digitally and viewed on an X-ray workstation in or near the trauma bay.

2.1.7. Wall charts and Broselow tape

Wall charts provide information on treatment parameters by patient age and weight, as well as the normal ranges of patient vitals by age and weight. To aid in the management of injured children, the Broselow Pediatric Emergency Tape provides a length-based estimate of medication doses, dose delivery volumes, and equipment size using color-coded zones.

2.1.8. Other equipment

Cabinets along the walls are filled with instruments and equipment used for patient evaluation and treatment. There are containers of sterile water for irrigation, scalpels, dressings, gauze, sponges, syringes, lines and tubes of various sizes, and bags of crystalloid solutions. Medications and blood products are also kept nearby in refrigerators and cabinets. Physicians and residents carry stethoscopes for chest auscultation and trauma shears for clothes removal.

Although most instruments in trauma resuscitation are associated with a unique task, several tools can be used jointly to perform a single task. For example, the laryngoscope, ET tube and CO_2 detector are used only during patient intubation. In our work, we exploit this feature of trauma work to detect and recognize team activities. We argue that accurate detection of one tool is sufficient to recognize most tasks. In contrast, the otoscope can be used for both assessing the patient's pupils (essentially used as a flashlight) and ears (used for its intended purpose). Such rare cases of multipurpose tools need to be treated with probabilistic object-task associations.

3. Current study

3.1. Research setting

Our study took place at Children's National Medical Center (CNMC), a pediatric level 1 trauma center in Washington, DC. CNMC is the only hospital in District of Columbia metropolitan region dedicated to the care of children. The hospital serves the DC metropolitan region and admits over 1000 injured patients each year, about half of whom are initially treated in the trauma bay. Patients are treated in one of the two trauma bays equipped with medications and equipment. Both trauma bays have a high-resolution recording systems installed that include two ceiling-mounted cameras and microphones, and direct digital output from patient monitors. This study was approved by the hospital's Institutional Review Board (IRB) as an exempt protocol.

We installed off-the-shelf RFID equipment in our university laboratory and in the trauma bay at CNMC. UHF RFID readers (ALR-9900) were acquired from Alien Technology [28]. These readers operate at 915 MHz and provide both the received signal strength indication (RSSI) and the binary detection information. We chose circularly polarized antennas (ALR-9611-CR, 3 dB beam width of 65°), also from Alien Technology, to reduce the effect of their orientation on read performance as they radiate energy in horizontal, vertical and all in-between planes. Passive RFID tags came from several vendors, including Alien Technology, Avery Dennison and Confidex. The tags varied by size and shape (e.g., rectangular, long, and thin) and were powered by the signal transmitted from RFID readers.

3.2. Methods

Finding the optimal placement for RFID tags and antennas required an analysis of the trauma bay environment, object shapes and sizes, as well as providers' interactions with patients, medical tools and equipment. We also needed to develop guidelines for signal interpretation to identify whether an object was stationary, in use, or carried. To accomplish these goals, we performed three types of analyses: (1) classification of tasks and objects using task analysis; (2) description of objects using content analysis of equipment photographs; and (3) description of providers-objects interactions using analysis of videos of simulated resuscitations.

3.2.1. Task analysis

To define the objects and key personnel involved in different resuscitation tasks, medical experts on our research team performed task analysis. We focused on the primary survey because this portion of trauma resuscitation is most important and consistent between providers and from patient to patient. We also reviewed the medical literature to determine standards and best practices for each component of the primary survey. The task analysis yielded over 300 separate tasks, with providers' roles and objects assigned to each task. To ensure the accuracy of the task analysis, a physician and nurse who did not participate in its initial construction revised the task analysis using a consensus approach.

To better illustrate the task analysis, we provide a sample of the completed task analysis for airway management task (Fig. 1). Airway management is a hierarchical task consisting of five levels and approximately 150 subtasks. Some tasks are constraint-dependent, which is indicated by the plan specified next to the ancestor task. For example, assessment of the airway is mandatory, while airway management is required only if the airway is compromised (Fig. 1, left). Each task contains a set of subtasks with clearly defined order, steps within a subtask, key personnel, and medical tools and equipment. For instance, patient intubation, or ET tube insertion, is a level 4 task in the airway management sequence of tasks (Manage airway → Establish definitive airway → Orotracheal intubation → ET tube insertion). It consists of seven subtasks, each being done by either an anesthesiologist or a respiratory technician and involving a set of airway tools (Fig. 1, right).

Analysis of resuscitation tasks provided the needed input required for personnel and object tracking. In addition, the knowledge acquired through the task analysis allowed us to focus our

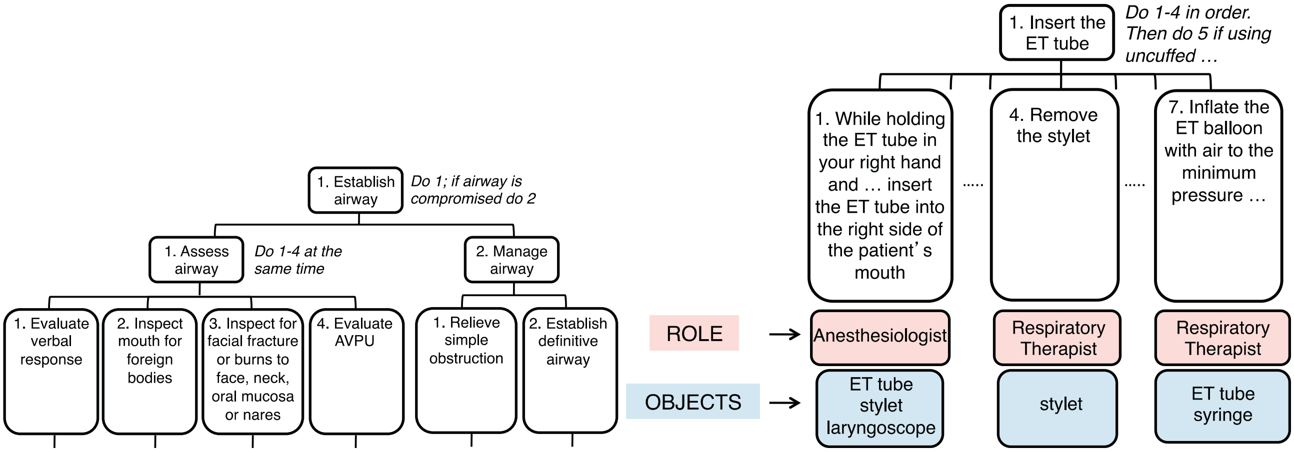

Fig. 1. Snapshots from task analysis diagram for Airway step in the ATLS protocol. Left diagram shows the top three task levels. Right diagram shows subtasks (level 5) for patient intubation task (level 4), along with key personnel and required medical tools.

analysis of videos on particular providers-objects interactions, their duration, and frequency.

3.2.2. Content analysis of equipment and room photographs

Over the course of our study, we took a total of 88 photographs, 63 of which show commonly used medical tools, supplies and equipment, and 25 show the trauma bay. The photographs were uploaded to a photo-sharing site accessible to all members on our research team. We used photographs of the room to assess the environment and identify locations for RFID antennas. Photographs of the objects were used to determine the tag type and identify locations for tags by assessing the object size, shape and composition. Experts in trauma resuscitation annotated photographs of objects, providing the following information for each object:

- *Object*: Name of the tool, supply item or equipment.
- *Purpose*: Description of the task that the object is used for.
- *Material*: General composition of the object.
- *Other material*: Other materials that compose the object. For example, pleural bags fill with blood when in use.
- *Wrapping*: Whether the object is wrapped. If wrapped, description of the wrapping material.
- *Taggable*: Whether the object is taggable itself or has the wrapping.

Selection of an appropriate RFID tag type required an analysis of object size and shape, as well as the materials and composition of the object. We used information about the object shape and size to identify available surfaces for tag placement. Information about whether an object is taggable was used to indicate if the object could be tagged directly or on a plastic wrapping. If the object is wrapped, the tag can only be placed on the wrapping, which limits the degree to which the object can be tracked.

3.2.3. Review of simulated resuscitation events

To enable interpretation of radio signals from tagged objects and infer whether an object is in use, stationary or carried, we analyzed video recordings of simulated resuscitation events to better understand providers' interactions with medical tools and equipment. We reviewed 13 videotaped simulations with an average duration of 10 min. To aid the analysis, we also transcribed the videos. Transcripts included the list of high-level tasks (e.g., suction applied, intubation started) along with timestamps and key personnel involved in performing those tasks. We focused our video analysis on the following features of work: (1) the manner in which tools and equipment are used during evaluation and treatment procedures; (2) frequency and duration of interactions with tools; (3) current placement and storage of medical tools and equipment; and, (4) spatial distribution of tools and medical personnel during resuscitations. Notes from video reviews were collated and analyzed for tools usage patterns.

4. Findings

Our findings are structured based on the three research goals. First, we present the results from the task analysis that helped us identify tasks and objects that need tracking. We then present our results from laboratory experiments, as well as the results from the analysis of photographs and videos that guided the placement of RFID antennas and tags in the trauma bay. Finally, we present the guidelines we developed for interpreting radio signals from tagged objects.

4.1. Tasks and objects for RFID tracking

Based on the results from task analysis, we created a list of resuscitation tasks, objects and personnel for tracking in collaboration with a group of representative members from each role on the trauma team (e.g., physicians, nurses and respiratory therapists). Although the task analysis yielded over 300 separate tasks for the primary survey, our list focused on a subset of tasks that were judged as important for the performance of trauma resuscitation; if omitted or performed incorrectly, these tasks could lead to adverse patient outcomes. In addition, we excluded lower-level subtasks because detecting them is practically and computationally more challenging. For example, medication administration can occur throughout the primary survey and is an important task. Detecting medications, however, poses several challenges: the number of medications is quite high; medications are often liquid and stored in vials, and liquid interferes with the radio signal; vials are discarded after medications are drawn, which also requires tagging syringes and matching them with container tags. We plan to address these challenges in our future work.

Our final list of primary survey tasks, along with required objects (O) and personnel (P), as determined by the task analysis, included: *neck immobilization* (P: physician right, primary nurse; O: cervical collar), *assessing and managing the airway* (P: team leader, physician right, anesthesiologist, respiratory therapist, technician; O: laryngoscope, ET tube, CO_2 detector), *assessing and managing respiratory status* (P: team leader, physician right, primary nurse, respiratory therapist, technician; O: stethoscope, chest tube, device for drainage of the pleural cavity), *obtaining vital signs* (P: surgical resident, primary nurse, technician; O: monitoring equipment and sensors, manual BP cuff, thermometer), *oxygen administration* (P: anesthesiologist, respiratory therapist; O: face mask, bag valve mask), *placing cardiac-respiratory monitor or defibrillator* (P: primary nurse; O: ECG leads, pulse oximetry probe), *assessing circulatory status* (P: physician right, primary nurse; O: IV equipment and supplies), *assessing neurological status* (P: physician right; O: otoscope, ophthalmoscope), *patient exposure* (P: primary nurse, technician; O: trauma sheers), and *estimating patient weight* (P: primary nurse; O: Broselow tape). There was no need to tag vital signs monitoring equipment and their sensor probes because their status can be captured from and observed on the vital signs monitor.

The presence and location of medical personnel provides valuable cues for detecting and recognizing tasks. For instance, presence of an anesthesiologist at the head of the bed strongly suggests that an airway management task is being performed. We can detect the presence of team members by attaching RFID tags to their employee badges. The challenge here is that badges are carried under protective gowns or in pockets, which affects signal reception. An alternative is to attach RFID tags to team members' role tags. Role tags are wearable, self-adhesive paper tags indicating each member's role during trauma resuscitation. At CNMC, team members attach their role tags to protective gowns. While the practice of wearing role tags is not common across trauma centers, we decided to track personnel via role tags for improved signal detection. Tagging personnel requires high performance passive RFID tags due to their close proximity to human body.

4.1.1. Constraints for RFID-based object tracking in trauma resuscitation

Our analysis of tasks and work procedures showed that finding the optimal placement for RFID tags and antennas in the crowded space of the trauma bay is subject to several constraints (Table 1). These constraints can be grouped into two categories based on their cause: (1) human factors, such as providers' movement,

Table 1
Constraints for RFID-based object tracking in trauma resuscitation.

	Human factors/constraints	Environmental factors/constraints
RFID antennas placement	• Crowded room with many people moving • Concentration of people around the patient bed • Occlusion of objects by providers' hands and body	• Crowded space, with walls covered by cabinets and drawers • Surgical lights suspended from ceiling • Radio interferences with medical equipment • Esthetics • RFID adoption costs
RFID tags placement	• Variable handling of objects • Occlusion of object tags by providers' hands and body • Tags may render objects uncomfortable for use	• Large number of objects • Variable object sizes • Variable object materials • Variable object shapes • Variable object packaging • Unreliable tag adherence

object occlusions by hands and body, and variable handling of objects; and (2) environmental factors, such as room size, spatial distribution of equipment, and esthetics of the room.

4.2. RFID antennas placement in the environment

To find the optimal placement for RFID antennas, we performed an analysis of the trauma bay using photographs and videos of simulated resuscitations. Our analyses focused on the spatial distribution of medical equipment, identifying locations of objects in use, and on positioning of providers during tasks. Based on these analyses, we divided the space of the trauma bay into five zones (Fig. 2): patient-bed zone, right and left zones, and foot and head zones. When in use, objects appear in the patient-bed zone; when stored, carried or left idle, objects appear in the left, right, foot or head zones. These five zones are typical for most trauma bays at major trauma centers. We then used these five zones as the basis for identifying the optimal placement for RFID antennas.

4.2.1. Requirements for RFID antennas placement

To maximize readout rates and increase accuracy of task detection and recognition, placement of RFID antennas in a high-risk medical environment should meet the following requirements:

1. Each zone should be covered by the field of view of at least one antenna. This requirement, however, does not imply that at least one antenna should be assigned per zone.

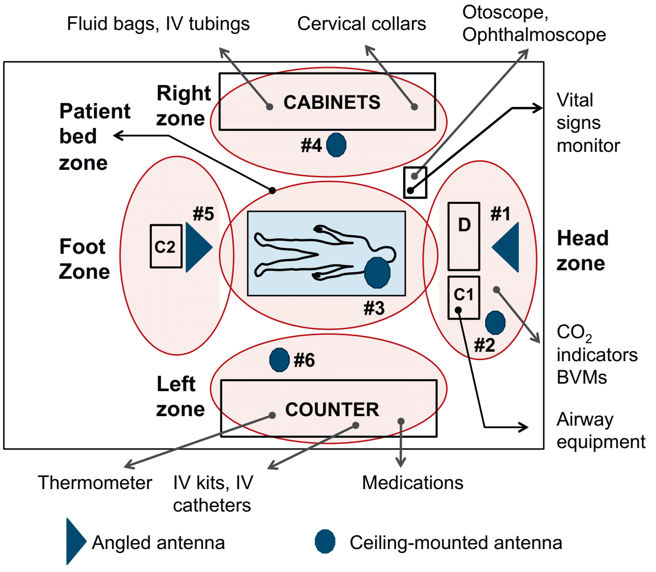

Fig. 2. Environmental setting of the trauma bay. Primary zones, locations for medical tools, supplies and equipment, as well as antenna positions are also indicated.

2. Antennas should be placed so that their reception and readout rates are minimally affected by random orientation and placement of tagged objects within the coverage area.
3. Antennas should be placed so that providers' movements minimally obstruct the visibility of tags to antennas during work. Ceiling-mounted antennas often meet this requirement, except when providers lean towards the patient and accidentally cover the object. Angled antennas, on the other hand, are more likely to be occluded by providers.
4. The number of deployed antennas should be minimized to reduce costs, mutual interference between antennas, radio interference between antennas and the hospital equipment, and to meet the esthetical requirements (Table 1).
5. RFID antennas and readers should be placed so that they do not restrain provider movement.

4.2.2. Evaluation of RFID antennas setups

Experimental setup: To evaluate different locations of antennas in the environment, we used our laboratory to recreate the actual setting of the trauma bay. Because objects during resuscitation appear either in the patient-bed zone or in storage zones (left, right, foot or head), we ran our experiments using two zones only: the patient-bed zone (the main work area) and the left zone (selected as one of storage areas). Each experimental zone was represented by a 0.9 m high cart. The carts were initially positioned 2 m away from each other, but then shifted during the experimental scenarios.

Our baseline setup #1 (Fig. 3) included a single floor-facing, ceiling-mounted antenna, positioned between the two zones, at 2.7 m above the floor. The area covered by this ceiling-mounted antenna was determined based on the antenna radiation pattern provided by the vendor. We made a conic beam approximation (a cone with its vertex on the transmitting antenna and its axis along the transmission direction) for the directional radiation pattern of the antenna. The 3 dB beam width (65°), also specified by the vendor, was used as the aperture angle of the cone [32]. The resulting coverage area was a circle with a radius of 1.5 m, at the distance of 1.8 m from the antenna. It is also assumed that radio signal attenuates according to inverse quadratic law by distance from the antenna source. The antenna covered both zones, meeting the first requirement, as outlined above.

Setups #2 and #3 (Fig. 3) included two ceiling-mounted antennas at the same height to capture differences in received radio signals, which helps in distinguishing between object movements (the more antennas in the environment, the more diverse information about the object because of differing vantage points of antennas). In setup #2, antennas were positioned directly above the zones, whereas in setup #3, antennas were positioned on a line perpendicular to the line connecting the zones. In setups #4 and #5, we increased the number of antennas by two and four, respectively. To account for the variability in object and tag orientation

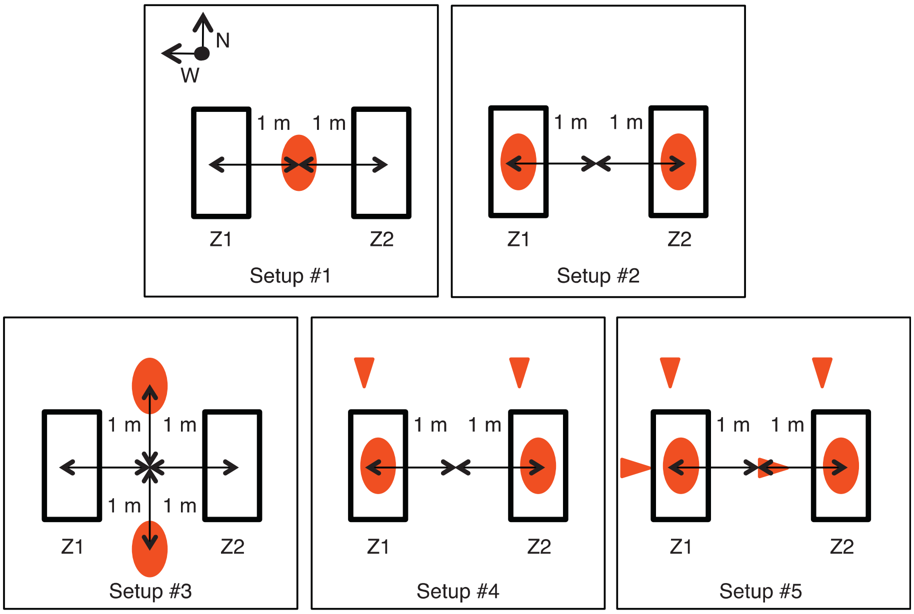

Fig. 3. Top view of five different antenna setups. Z1 represents the patient-bed zone and Z2 represents the left storage zone. Ceiling-mounted antennas are shown with circles; angled antennas are shown with triangles.

(our second requirement), we angled antennas so that they transmit through different, ideally perpendicular, directions. To maintain the visibility of tags to antennas and to minimize interference with providers' work (our third and fourth requirements), we positioned antennas as high as possible. Assuming an average human height of 170 cm, all angled antennas were mounted at the height of 2 m and at an angle of 60° to the floor to cover the work area.

Experimental scenarios: We evaluated the robustness of different antenna setups using four experimental scenarios designed to simulate environmental characteristics of trauma resuscitation. To control for these characteristics, the scenarios did not include simulating the trauma resuscitation process. The process was studied during simulations in the actual trauma bay at CNMC, as described later (Section 5).

- **Scenario #1**: Stationary environment.
- **Scenario #2**: Deviations in zone locations: Although zone locations are relatively fixed (e.g., cabinets along the walls, patient bed in the center of the room), the exact locations of the patient bed and equipment carts may slightly shift over the course of resuscitation. To simulate deviations in zone locations, we moved the carts in the following directions:
  (2a) Zones Z1 and Z2 moved 0.6 m to north (distance between zones remained unchanged).
  (2b) Zone Z1 moved 0.6 m to north and Z2 moved 0.6 m to south (distance between zones increased).
  (2c) Zone Z1 moved 0.6 m to east and Z2 moved 0.6 m to west (distance between zones decreased).
- **Scenario #3**: Changes in object orientation: By default, objects were always facing the ceiling. To simulate random orientation of objects, we placed the object in two additional directions:
  (3a) Object was facing north.
  (3b) Object was facing west.
- **Scenario #4**: Changes in providers' mobility: Providers' mobility was simulated as follows:
  (4a) Two people moving around zones.
  (4b) Five people moving around zones.

We ran 70 experimental sessions, each repeated five times, yielding a total of 350 sessions. We experimented with two object states: (1) relocation between zones, and (2) movement (still vs. moving). Each session consisted of a 20-second RFID data recording, with object state changing at the 10th second. To simulate relocation between zones, we moved the object from zone Z1 to Z2 at the 10th second. To simulate movement change, we kept the object still for 10 s and then interacted with it for another 10 s. Scenario #2a was not performed for object motion because zones Z1 and Z2 were not moved relative to each other. Scenario #4b was also not performed for object motion because the experiment required multiple participants and results from object location experiments sufficed. We experimented with two metrics for measuring distance between statistical distributions of tag signals, Kullback–Leibler [33] and Mahalanobis [34], to ensure that our experimental results are not metric-dependent.

Experimental results: Our results showed that the sensitivity of received radio signals to object state changed for different antenna setups (Fig. 4). The lighter the color in the matrix, the more sensitive the antenna setup was to the object state change. For both object states, the sensitivity increased with more antennas. Although setups #2 and #3 had two antennas, setup #2 was more sensitive because antennas were positioned directly above the zones. Based on these results, we believe it is necessary to have at least one designated ceiling-mounted antenna per work zone, placed in the center of the zone. Adding more antennas would provide greater sensitivity, but would go against other constraints (Table 1). Our results also showed that the sensitivity of different antenna setups to object state was greater for relocation than for movement. These results imply that location changes are easier to detect compared to movement at the same location (e.g., movement of laryngoscope from the cart to the patient bed vs. movement of laryngoscope while the physician is inserting an endotracheal tube).

4.2.3. RFID antennas placement in the actual trauma bay

Our experiments showed that achieving optimal coverage and reliable detection of signals from tagged objects required placing at least one floor-facing, ceiling-mounted antenna in the zones where objects appear frequently. We placed four such antennas

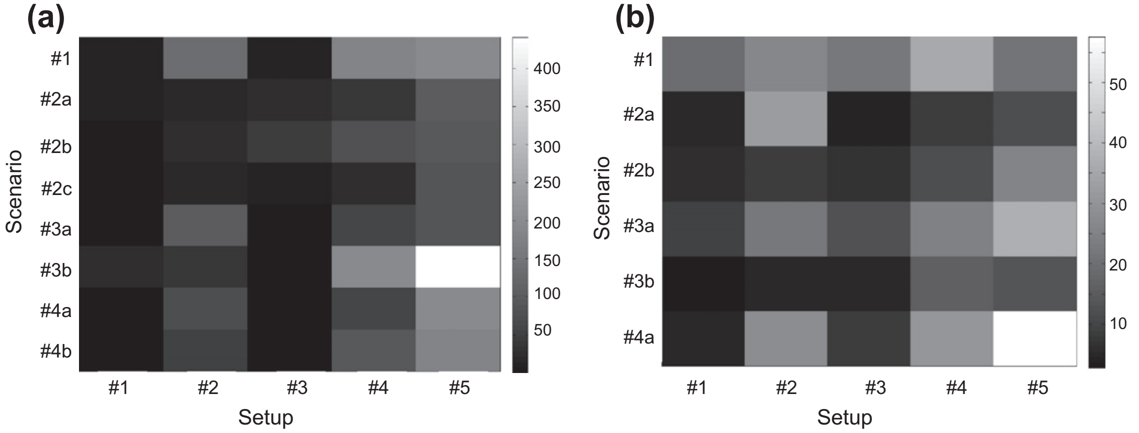

Fig. 4. Heatmaps showing the sensitivity of received radio signals to object state change for five antenna setups. (a) Object relocation between zones. (b) Object movement (still vs. moving). Notice the difference in range of values for heatmaps.

Fig. 5. Positioning of angled and ceiling-mounted antennas at CNMC. Left picture shows angled antenna #1. Right picture shows ceiling-mounted antenna #3.

at 2.7 m above the floor (Fig. 2, circles): one in the head zone (#2), one in the patient-bed zone (#3), one in the right zone (#4), and one antenna in the left zone (#6). The actual deployment of antenna #3 is shown in Fig. 5, right. We added two angled antennas to cover the patient-bed zone for improved signal detection rates and for increased accuracy of localization and movement detection (Fig. 2, triangles). Although we installed these antennas in the head zone at 2.3 m (antenna #1 in Fig. 2) and in the foot zone at 2.5 m (antenna #5 in Fig. 2), they were facing, and thus covering, the patient-bed zone. The actual deployment of antenna #1 is shown in Fig. 5, left. Because the foot zone is rarely used for placing or using objects, we did not scan this area for signals.

The theoretical radius for each of the five major detection zones is about 2.2 m on the floor and about 1.5 m on a plane level, roughly 0.8 m above the floor to detect objects that are carried or placed on the patient bed. Although antennas can detect tags that are outside the five major zones, probability of detection will decrease.

To speed detection of radio signals, the antennas can be connected to multiple RFID readers that can operate simultaneously. In this configuration, each reader must cycle through the active antenna ports in a round-robin fashion and the reader-antenna connections must be assigned to minimize the interference. We placed two RFID readers in the trauma bay, hidden in the space above the ceiling. Antennas #1, #2 and #3 are connected to the first, second, and third port of the reader 1, respectively, and antennas #4, #5 and #6 are connected to the first, second, and third port of the reader 2, respectively. This connection scheme allows antennas to be active sequentially in pairs 1–4, 2–5 and 3–6. To reduce signal interference, the antennas scanning the patient bed are never active at the same time.

4.3. RFID tag types and placement in the environment

Content analysis of photographs provided the needed input for determining the type of RFID tags as well as their potential placement on objects. To develop guidelines and strategies for tags placement, we conducted preparatory experiments in our laboratory before deploying the RFID system in the trauma bay.

4.3.1. Requirements for RFID tags placement

Previous research has shown that the detection rate of passive RFID tags depends on many factors [29–31]. To maximize object detection rates, deployment of tags in a time-critical medical setting should meet the following requirements:

1. Each object should have at least one tag. It is also possible to attach tags to kits or trays to represent a group of objects used to perform a particular task, such as IV kits or intubation tray. Tagging individual objects, however, allows for information integration from multiple objects, which improves the overall task recognition.
2. Tags should be placed so that they remain visible to RFID antennas, regardless of the orientation of the object.
3. Tag shape should be preserved when attaching it so that its antenna can function optimally (e.g., if the tag is folded, its antenna may not reflect well the signal from the reader).
4. When tagging objects made of metal or filled with fluid, it is important to minimize the contact between the tag and the

object. While these limitations can be addressed using special tags for metal or liquid, their cost is higher.

5. Tags should be placed on the object parts that are not in contact with providers' hands or body, to avoid occlusion.
6. The number of tags should be minimized to reduce costs, potential message collisions during tag-reader communication, and to preserve esthetics of the object (Table 1). Previous work has shown that RFID readers can detect less than hundred tags at a time [29].
7. Tags should be placed so that they do not render objects uncomfortable for use.

4.3.2. Evaluation of tag types and tagging strategies

Experimental setup: To evaluate different tag types and strategies for their placement on objects, we performed a set of experiments in the two-zone setting (introduced in Section 4.2.2). The storage area (zone Z1) was scanned by one ceiling-mounted antenna, and the patient-bed area (zone Z2) was scanned by one ceiling-mounted- and two angled antennas. This experimental setup is a combination of antenna setups #2 and #5 (Fig. 3). We experimented with a set of objects representing a variety of materials, sizes and shapes found in the trauma bay, including a stethoscope, cervical collar, Foley catheter, and an intravenous fluid bag.

Experimental scenarios: We evaluated different tag types and strategies for their placement using three experimental scenarios that focused on specific cases, such as tagging liquid containers and objects with narrow cylindrical surfaces.

- *Scenario #1*: Tag type and placement based on object material: A major limitation of passive RFID tags is their poor performance on objects made of metal or filled with liquid. Off-the-shelf on-metal tags are not appropriate for disposable objects because of their cost. Objects that contain liquid, such as fluid bags or medication vials, can be tagged with regular tags, but the tag should be attached so that contact with liquid part is minimal [29]. For example, tags can be attached to the seam of an intravenous fluid bag. We evaluated this approach first by attaching the tag along its length, and then by attaching the tag along its width.
- *Scenario #2*: Number of tags: Although a single tag may be sufficient to detect object presence and identity, it is usually insufficient for detecting state change (relocation and movement), which is our goal. Therefore, we used multiple tags for more reliable state detection. Having multiple tags is especially useful for irregularly shaped objects when the likelihood of occluding a tag by a hand or body is higher. To analyze readout rates for objects with more than one tag, we experimented with a Foley catheter kit, which has a regular box-like shape, and with a stethoscope, which has a thin, cylindrical surface.
- *Scenario #3*: Tag placement based on object shape: Most objects in the trauma bay have irregular shapes. This feature requires different strategies for placing RFID tags. For example, objects with cylindrical surfaces may require folding the RFID tag, which in turn may impair the radio signal reception. To examine the effects of tag folding on readout rates, we ran an experiment with a stethoscope, whose thin cylindrical surface required folding the tag. We experimented with four folding levels and styles: (1) no folding along the tag's width; (2) minor folding along the tag's width; (3) complete folding along the tag's width; and, (4) complete folding along the tag's length.

We ran 17 experimental sessions, each repeated five times, yielding a total of 85 sessions. Each session consisted of a 20-s RFID data recording, with object relocation occurring at the 10th second. We used the readout rate (number of readings collected from an object per second) as an evaluation metric. Data was collected in both zones to eliminate the zone-specific effects, e.g., the number of antennas scanning a zone.

Experimental results: Experiments with an intravenous fluid bag (Fig. 6a) showed that attaching the tag along its width yielded higher readout rates while also minimizing the object-tag overlap. Having more than one tag on an object improved readout rates from both the Foley catheter kit and the stethoscope (Fig. 6b). We also observed that readout rates improved as the distance between tags increased, or when the tags were placed at different orientations (Fig. 6b). Experiments with tag folding showed that folding a tag around the stethoscope caused degradation in readout rates for complete folding along the length and for all folding levels when the stethoscope was carried around the neck (Fig. 6c). Although complete folding along the tag's width reduced readout rates from ceiling-mounted antennas, reception from the angled antennas increased when the stethoscope was on the cart because part of the tag directly faced the antennas. We also observed lower readout rates when the stethoscope was around a subject's neck because being in proximity of human body (mainly composed of fluids) decreased readout rates (Fig. 6c).

4.3.3. Tags placement in the actual trauma bay

Our experiments showed that performance of RFID tags varies based on object material, size and shape. Tagging of objects in the trauma bay was thus based on the information about object composition and materials, their shape and their size (Fig. 7). For

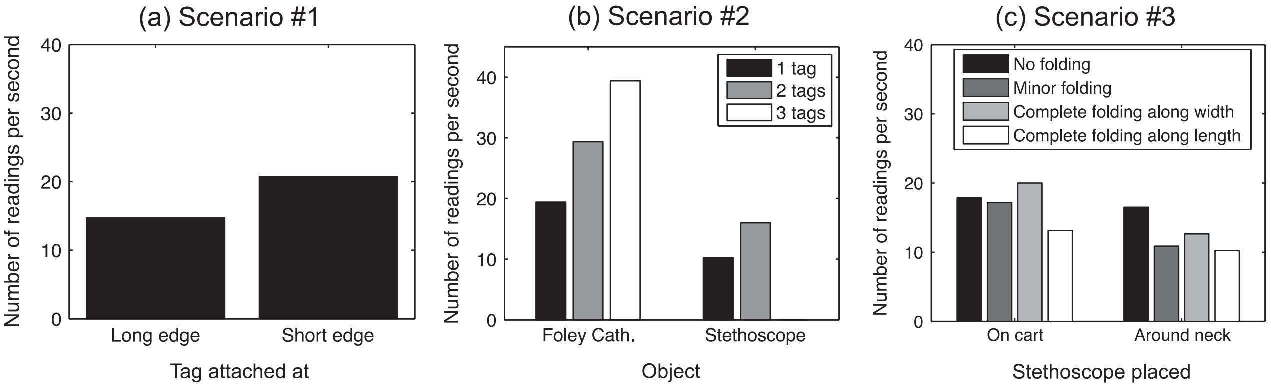

Fig. 6. Experimental results for tag types and tagging strategies: (a) Scenario #1: Tag placement based on material. (b) Scenario #2: Effects of having multiple tags. (c) Scenario #3: Effects of tag folding.

Fig. 7. Example tagged objects: intravenous fluid bag (left); thermometer (middle); stethoscope (right). RFID tags are circled.

example, the laryngoscope is made of metal and requires special on-metal tags. Putting a regular tag on a metallic object yields no signal and the object cannot be detected. Sterile objects with plastic wrapping, as well as objects made of plastic were tagged using regular tags.

Because performance of an RFID tag is proportional to its size, we used the largest possible tag. The size of the tag, however, depended on the available surface for tagging. For example, an otoscope is a small and cylindrical object composed of both metal and plastic. It requires either a small tag or folding a larger tag around the object. When the optimal tag position corresponded to a metallic part of the object, we used on-metal tags. Similarly, the thermometer requires different tag sizes for optimal tracking. The base was tagged using a larger tag, while the probe required folding a small tag around it (Fig. 7 (middle)).

Although passive RFID tags provide only proximity information, using multiple antennas allowed obtaining proximity information from each antenna. By comparing the numbers obtained from each antenna and then identifying the closest antenna, we could accurately predict in what zone the object lies. Because our goal is to infer zone-based information rather than exact coordinates for each object, we found passive RFID tags adequate for this task.

4.4. Cues for identifying objects in use

Results from video analysis of simulated resuscitations showed that interactions with medical tools and equipment during resuscitation tasks are complex and involve different usage patterns, depending on the object and task. Using an object means fetching it from its current storage place, interacting with it for some time, and then returning it back to its place. Our results showed that the object-use cycle is more complex in practice because the process is error-prone and tasks are performed collaboratively. For example, a nurse may retrieve an ET tube but realize that a different size is needed and returns it without using it.

To better illustrate the object-use cycle during resuscitation tasks, we provide two examples of object use that we observed in videotaped trauma resuscitation simulations at CNMC. First, we describe the use of thermometer. Upon learning of an incoming trauma patient, members of the team gather in the trauma bay and start preparing equipment based on anticipated patient needs. Because patient temperature is measured during the first few minutes after patient arrival, the primary nurse fetches the thermometer from its storage location (above counter) and places it on the cart (C2) at the foot of the bed (Fig. 2). The nurse then proceeds with preparing other tools to make them available during patient evaluation. The thermometer remains on the cart for about four and a half minutes until the team leader asks for the temperature measurement. The nurse fetches the thermometer again and starts measuring the patient's temperature. At this point, the thermometer is in the patient-bed zone. After using the thermometer for about 20 s, the nurse puts it back on the cart, where it remains until the end of the simulation.

Our second example shows the use of laryngoscope. The laryngoscope is located on the cart (C1) in the head zone (Fig. 2), along with other airway equipment. After being asked by the team leader to intubate the patient, the anesthesiologist fetches the laryngoscope from the cart, places it at the head of the bed and proceeds with preparing other tools. Shortly after, the anesthesiologist starts intubation, stops for about 20 s to ventilate the patient, and then continues intubation for another 50 s. During this time, the laryngoscope is in the patient-bed zone. In addition, the laryngoscope experiences slight movements as the anesthesiologist attempts to place the blade correctly. Upon completing the task, the anesthesiologist leaves the laryngoscope on the bed (patient-bed zone), where it remains for another 8 min. The usage patterns for both the thermometer and the laryngoscope were observed across all videotaped simulations that involved the use of these objects.

Using the above approach, we analyzed usage patterns for all objects that were marked for tagging. Based on these analyses, we identified three cues indicating that an object is in use:

1. *Zone-based location*: Objects in the patient-bed zone are more likely to be in use than objects located in the foot or head zones (carts), or in the right (cabinets, trays along the wall) and the left zones (counter).
2. *Motion*: Objects in motion are more likely to be in use than idle objects.
3. *Contact:* Interaction or contact with an object indicates that the object is likely to be in use.

4.4.1. Zone-based location cue

Resuscitation tools, supplies and equipment are stored at different locations in the room: in cabinets and drawers, on trays and carts along the walls, or attached to the walls (Fig. 2). When needed, these objects are taken to different locations depending on their purpose (relocation). Using the location-based information, we can classify the objects into three groups.

(a) *Objects brought to the patient-bed area before use*: Some objects are taken from their storage places before patient arrival, during the preparation phase or shortly upon patient arrival during the patient handover. These objects are placed on the patient bed or on the cart in the foot zone for an easy reach during patient evaluation. Objects that are brought to the patient-bed area before use include monitoring equipment, thermometer, IV toolkit, intravenous fluid bags, and manual blood pressure cuff.

(b) *Objects brought to the patient-bed area when needed*: Most objects are brought to the patient-bed area when needed. For example, intubation equipment is readied for use if the patient's airway is compromised; a chest tube placement tray is prepared if a severe chest injury is suspected; and, warm blankets are applied if the patient is hypothermic.

(c) *Objects prepared outside the patient-bed area*: Wrapped items, such as tubes, syringes, needles, and CO_2 detectors are unwrapped in the patient-bed area to minimize contamination. These objects may also be unwrapped outside the patient-bed area where tagged wrappings are thrown away or dropped on the floor. We observed that even if unwrapped away from the patient-bed zone, the objects are immediately brought near the patient because sterile items must be used shortly after removing the wrapping. Medications can also be included in this category because they are prepared at the counter (in the left zone) and then brought to the patient-bed area for administration.

Zone-based location is an important cue for detecting objects in use, but this cue can sometimes lead to misinterpretation of radio signals. For instance, if the object is brought to the patient-bed area long before usage, identifying in-use time based on location only is difficult. To detect in-use time for those objects, we also need to take into account information about motion and contact. Similarly, location cue alone cannot be used for detecting in-use time for wrapped objects that are prepared (being unwrapped) outside the patient-bed area because their tagged wrappings are either thrown away or left there.

4.4.2. Motion cue

While in use, some objects may experience slight movements. For example, the automatic blood pressure cuff moves as it inflates during BP measurements; the laryngoscope moves as the anesthesiologist places the blade; and, the otoscope and ophthalmoscope move as the physician examines pupils and ears. In contrast, some objects such as the cervical collar and intravenous fluid bags are still while in use. We use this information about object movement to further determine whether an object is in use. Based on their motion status, objects can be classified into two categories:

1. *Moving while in use*: Objects in this category experience slight movements while in use. These include: laryngoscope, otoscope, ophthalmoscope, Broselow tape, oxygen masks, stethoscope, manual and automatic BP cuffs, thermometer, intraosseous line (IO) placement gun, and wrapped objects such as tubes, CO_2 detector, Foley catheter, IV toolkits, IV catheters and IV tubing. Although some wrapped objects remain still after placement (e.g., tubes and catheters), we categorize them as moving because we can only tag their wrapping and detect those tags as the objects are being unwrapped.
2. *Standing still while in use*: Objects in this category are still while in use and include cervical collars and fluid bags.

4.4.3. Contact cue

Using an object implies that either a provider or patient is in contact with that object. If we attach an RFID tag at the point where the tag will be covered by provider's hand or patient's body, the RFID signal will disappear when the contact starts because human body absorbs the signal. We can exploit the behaviors of RFID tags during this contact as an additional cue for detecting objects in use. This approach, however, requires sufficient duration of contact for reliable detection. Based on the observed duration of contact with different objects, we divide objects as follows:

Brief contact: Contact with an object is brief, up to 10 s. Objects characterized by brief contact include wrapped (sterile) items such as tubes, CO_2 detectors, Foley catheters, syringes, and needles. Because sterile objects cannot be tagged directly, RFID tags can only be placed on the outside wrapping. The contact is therefore considered brief because it occurs during unwrapping; tags on the wrapping are readable only for a brief period of time, as the object is being unwrapped. Once the object is unwrapped, the tags are lost and cannot be used for object detection anymore.

Long contact: Contact with an object is longer than 10 s. Long contact was observed for objects used or touched by both patients and providers:

(a) *Patient-object contact*: These objects are in contact with the patient's skin when in use. The duration of this contact is long, often throughout the whole resuscitation event. Once an object is placed on the patient, it stays there until the patient is moved to another hospital unit. Objects in this subcategory include cervical collars, automatic BP cuff, pulse oximeter, ECG leads, oxygen masks, warm blankets, and the patient bed itself. An exception is the manual BP cuff that is used only for the initial BP measurement and then removed.

(b) *Provider-object contact*: These objects are in contact with the provider's body or hands when in use. The duration of this contact is shorter than patient-object contact because providers move around frequently and perform different tasks. Objects in this subcategory include the stethoscope, thermometer, laryngoscope, ophthalmoscope, otoscope, Broselow tape, and other tools.

To exploit the contact information for object use detection, we propose placing two RFID tags *in tandem*: one tag at the point where the tag will be covered by provider's hand or patient's body when in use, and the other tag at the location where it will remain exposed when in use. When an object is not in use, we expect strong radio signal from both tandem tags; when an object is in use, the tag in contact with provider or patient will emit weaker signal or no signal at all. One caveat must be considered when detecting objects in use based on contact information. Due to the dynamic nature of work in the trauma bay, signals from tags may be lost briefly due to accidental contact or occlusion caused by human movement. Because distinguishing accidental from purposeful but brief uses of an object is almost impossible, we realized that we could not use contact cue for objects characterized by brief contact. We therefore decided not to tag these objects with tandem tags. To detect when these types of objects are in use, we needed to rely on zone-based and motion cues.

Examples of objects with tandem tags are shown in Fig. 8. Cervical collars belong to the long patient-object contact category, while the intraosseous line placement gun belongs to the long provider-object contact category. To detect the use of the cervical collar, we used the signal from the front tag (the back tag is in contact with the patient and non-detectable). To detect use of the intraosseous line placement gun, we used the signal from the tag on the box (the handle tag is occluded by hand).

4.4.4. Experimental evaluation of tandem tagging for capturing contact information

We evaluated tandem-tagging approach using a cervical collar and a stethoscope. We first tagged each object with two tags so that tags were exposed to antennas at all times. We then tagged both objects with two tags in tandem, so that one tag was always exposed and the other became covered when the object was in use. During the first 10 s of a data recording session, the collar was placed in the storage area (zone Z1) and the stethoscope was hanging around the experimenter's neck in the patient bed area (zone Z2). During the remaining 10 s, the collar was relocated from the storage to the patient bed area and was placed around a subject's neck, covering one of the tags; the stethoscope was used for breath sounds examination, with the experimenter's hand covering the tag near the stem. We compared the received signal strength indication (RSSI) produced by different tag configurations by

Fig. 8. Example objects with tandem tags: front (left) and back (middle) of a cervical collar; intraosseous line placement gun (right); RFID tags are circled.

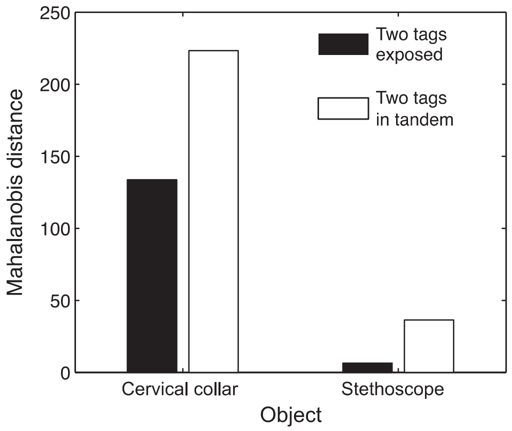

Fig. 9. Experimental results for tandem tags placement.

Table 2
Interaction types and statistics for airway equipment across five simulations. Average, minimum and standard deviation of interaction duration given in seconds.

Interaction type	#Interactions	Avg. duration	St. dev. duration	Min. duration
Laryngoscope				
Relocating	7	1.7	0.5	1
Holding (no use)	7	6.8	4.1	2
Using	5	54	42.5	24
ET tube				
Relocating	7	1.7	1.2	1
Holding (no use)	4	16	16.9	4
Using	5	24	22.9	4
CO_2 detector				
Relocating	4	3.3	1.9	2
Holding (no use)	1	1	n/a	1
Using	2	6.5	0.7	6

calculating the distance of their statistical distributions (Fig. 9). Our experimental results showed that configuration with two tags in tandem yielded higher distribution distance for both the collar and stethoscope (Fig. 9).

Objects characterized by short interactions can also be tagged using two RFID tags for more robust object detection. The goal here is to obtain robustness via redundancy: if one tag is not readable, the other tag can still be detected. It is important to separate the placement of tags to prevent radio coupling of the tags, which may distort the signal [35]. For objects with small surfaces, only one tag is needed to avoid the coupling effect.

4.4.5. Algorithmic detection of in-use cues

An algorithm can be developed to detect the presence of location-based, motion and contact cues, and identify objects in use. Each cue requires a different algorithm. To detect zone-based location of an object, the algorithm would search for an antenna that receives the strongest radio signal from object tags. To detect motion status, the algorithm would detect a significant change in standard deviation of signal strength received from object tags. To detect contact, the algorithm would monitor signal strength received from tandem tags: if the signal from one tag disappears while the other tag continues to emit strong signal, the object is likely in use. Information about these cues can then be integrated depending on their confidence levels; the cue with a higher confidence level has more weight on final decisions about object use.

4.5. Identifying false object use detection

Analysis of provider-object interactions showed that only a subset of interactions represents the actual object use. We observed that brief interactions almost always represented either relocating the object from one zone to another or holding the object without using it. To identify instances of false object use, we can derive distributions of duration for different interaction types (e.g., relocating, holding, using) for each object. If the distribution of duration of object use does not overlap with distributions of duration of relocating or holding, these non-use interactions can be distinguished based on their duration. As an example, we analyzed the use of airway equipment, analyzed across five simulations in which the patient was intubated (Table 2). The longest interactions were those of using objects for a task purpose while shorter interactions included relocating the object or unwrapping. For the laryngoscope, the average duration of actual use was 54 s, which is significantly longer than the average duration of holding the instrument, 6.8 s. Although standard deviation of 42.5 s may suggest an overlap between using and holding distributions, the minimum duration for using (24 s) indicates a right-tailed distribution and almost no overlap with the distribution of holding. Interactions with the laryngoscope shorter than 24 s can then be considered non-use interaction and filtered out. This threshold for short interactions is relative and depends on the object type. Because the CO_2 detector was used in one simulation only, the data for this object is limited and shows only minimal overlap between holding and using distributions (Table 2). Unlike for laryngoscope and CO_2 detector, statistics for holding and using distributions are similar for the ET tube, indicating a significant overlap between interaction types, thus the failure to filter out false detections of use. Because the laryngoscope and CO_2 detector are also used for intubation, and their false alarm rates are lower, our activity detection system is not directly affected by false detections of ET tube use. The example with airway equipment shows that tasks requiring multiple objects can be detected more reliably using interaction duration times than tasks requiring a single object.

Because our observations of interactions with objects were based on simulated resuscitations (where use of an object is often shorter than in reality), we believe that the differences between “relocating”, “holding” and “using” an object will be even more apparent in actual events.

5. RFID deployment at CNMC

We deployed our RFID tracking system in the trauma bay at CNMC and conducted experiments during eight simulated resuscitations to assess the feasibility of our approach. Each simulation lasted up to 15 min and included a diverse set of clinical conditions, patient types and tasks, including intubation, administration of fluids and medications, temperature control and chest tube insertion.

We tagged 48 objects: one otoscope, one ophthalmoscope, two cervical collars, one Broselow tape, two bag valve masks, four fluid bags, six IV toolkits, four IV tubings, 12 IV catheters, one orogastric tube, one Foley catheter, two stethoscopes, one BP cuff, one thermometer, one intraosseous line placement gun, the patient bed, and airway equipment (four ET tubes, one laryngoscope, and two CO_2 detectors). The number of tagged objects of each type varied by the simulation scenario and available equipment. For example, we tagged two cervical collars of different sizes because simulations involved different patient types. Because simulation sessions were performed using a plastic mannequin, we could not test the behavior of tags that are in contact with patient body. Before each simulation session, tagged objects were placed in their storage cabinets and drawers.

We also put RFID tags on the role tags of eight team members: team leader, physician right, anesthesiologist, primary nurse, scribe, medication nurse, respiratory therapist, and technician. Role tags were attached to protective gowns in the chest area. To assess the feasibility of tagging employee badges, we asked the primary nurse and respiratory therapist to carry RFID tags on their badges. The respiratory therapist’s badge was clipped to a waistband and the nurse’s badge was placed around the neck using a lanyard. We deployed a total of 84 RFID tags on objects and personnel combined, with an average of 72 tags per simulation session.

Two RFID readers with six antennas were deployed as depicted in Fig. 2 and described in Section 4.2.3. Although we installed the antennas and readers in an actual trauma bay, RFID scanning was active only during simulated resuscitations. The readers operated autonomously and were scanning the environment continuously at given intervals. An application on a host computer listened for notification messages from the readers containing tag data. The tag IDs indexed the database information about the tagged objects (entered manually by the experimenter).

5.1. RFID data rates from antennas in the trauma bay

Unlike controlled experiments in our laboratory (Section 4.2.2), in the actual trauma bay we could not control duration of different object states and the number of state changes. Therefore, we could not use the distance between statistical distributions of signals for evaluating different antenna setups. Instead, to assess the effectiveness of our antenna setups in the actual trauma bay, we measured the total number of readouts from each antenna during eight simulations (Fig. 10). Adequate readout rates are necessary although not sufficient condition for object use detection, which is our ultimate goal. Statistics from antennas depended on the environment, number of tags in antenna view and simulation scenarios. The first three antennas that were scanning the patient-bed and head zones captured most RFID data. Although antenna #5 was also scanning the patient-bed area, it generated fewer data rates due to its distance from the patient bed. Antennas #4 and #6 generated the fewest RFID readings. Antenna #4 was mounted above the cabinets (Fig. 2) and could not detect objects stored in the cabinets. When a team member took an object from the cabinet and carried it to the patient bed, antenna #4 could detect that object only for a short time. As a result, antenna #4 generated fewer data compared to other antennas. Similar results were observed for antenna #6 mounted above the counter. Because cervical collars are stored on top of the cabinets, most of antenna #4 readings came from the stored collars. In contrast, when a cervical collar was in use, the readouts came from antennas #1, #2 and #5. We are currently developing algorithms to exploit these changes in the reading pattern to identify tasks and objects that are being used during trauma resuscitation. Applying the object-use detection algorithms on RFID data captured from thermometer, we were able to identify 83% of use instances. Percentage of correct detections among all detections (“precision rate”) was 69% [36,37].

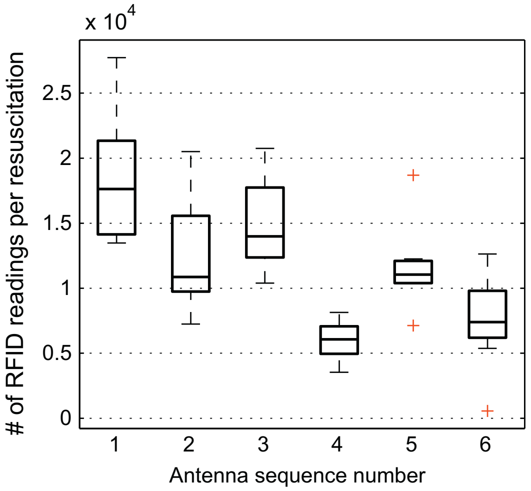

Fig. 10. RFID readings captured by six antennas over eight simulations. Central mark in the box: median. Edges of the box: 25th and 75th percentiles. Whiskers: most extreme data points not considered outliers. Plus sign: outliers.

5.2. RFID data rates from object tags

We measured the total number of readings from 19 tagged objects and people (Fig. 11). Of the 19 objects, six had one tag attached (Fig. 11a) and 13 had two tags (Fig. 11b). Our results showed that objects with two tags did not always provide higher combined readout rates than those with one tag. The reason is that, unlike the laboratory experiments, we could not control other confounding factors such as frequency and the duration of usage for different objects. Tag folding (indicated with an asterisk in Fig. 11b) impaired radio signal and reduced readout rates, as expected, except for bag valve mask (BVM), which is usually used throughout the resuscitation. Although these readout rates for most objects appear relatively small, the success rate of 83% that we achieved for detecting thermometer use indicates that even very small readout rates are quite good for object use detection. Higher readout rates may not be achievable given the limitations of current RFID technology and the complexity of the problem domain. To achieve higher use detection rates, RFID needs to be complemented with other sensory modalities, such as computer vision and motion sensors.

Among the objects that were always in view and used in all resuscitations, the fewest readings were observed for the otoscope,

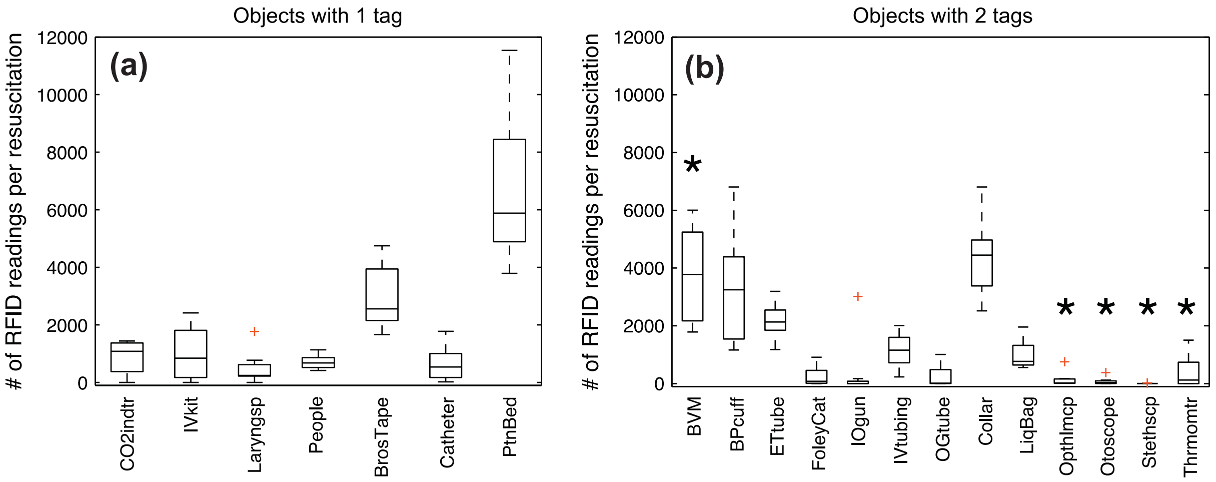

Fig. 11. RFID readings captured from tagged objects. (a) Objects with one tag. (b) Objects with two tags. Asterisks indicate objects with folded tags. Central mark in the box: median. Edges of the box: 25th and 75th percentiles. Whiskers: most extreme data points not considered outliers. Plus sign: outliers.

ophthalmoscope and stethoscope. The otoscope and ophthalmoscope set is mounted on a movable mechanical arm suspended from the ceiling. This arm is usually located between the zones monitored by the readers (Fig. 2). During simulations, the arm's location and orientation changed randomly as team members moved the set, which caused intermittent detection. In addition, both otoscope and ophthalmoscope are small objects with irregular shapes and composition, containing both metallic and plastic parts. To manage these issues, we bent the RFID tags around these objects, which impaired the radio signal. Similarly, the stethoscope has a small and irregular surface, posing significant challenges for RFID tag placement. Also, the stethoscope is usually carried around the neck and moves constantly, making it difficult to use motion cue for detecting its actual use. Finally, contact with human body and occlusion by hand and body when in use (physicians bend towards the patient during chest auscultation) cause additional signal interference.

Tracking the thermometer had similar problems. We attached two tags to the thermometer: one to the base and one to the probe. We used a small tag for the probe and bent it around the probe's small and irregular surface. Because of the issues with the probe tag, almost all readings for the thermometer came from the base tag.

In case of multiple objects of the same type but with different parameters (e.g., tubes of different sizes, fluid bags of different volumes or salinity), RFID technology offers advantages compared to other detection technologies. For example, computer vision algorithms have difficulty recognizing medical supplies because they are often made of translucent materials. In addition, vision algorithms cannot reliably determine objects parameters. In our experiments, we tagged four IV fluid bags. When a team member took an IV fluid bag from the cabinet, it was hung on an IV pole, which made the bag detectable. Even when an IV fluid bag was mistakenly fetched and returned back to the cabinet, we were able to detect this "false use" based on the duration of interaction. Our system also determined the fluid type and volume.

5.3. RFID data from personnel tags

We were able to detect all RFID tags attached to the paper-based role tags (see *People* in Fig. 11). The tag on the badge hanging around the nurse's neck was detectable rarely and the badge clipped to the respiratory therapist's waist was not detectable at all. These results showed that tracking personnel with passive RFID tags depends on the positioning of the tag on human body, which is consistent with previous findings [38].

6. Conclusion

The process of deploying RFID technology in the trauma bay was complex and required a careful design. We next summarize the challenges faced during our study and present guidelines for RFID antennas and tags placement in a time-critical medical setting. We conclude by discussing the use of RFID technology for tracking dynamic work processes.

6.1. Placement of RFID antennas

The placement of RFID antennas in the trauma bay was informed by our experimental results and by our analysis of the trauma resuscitation environment. We combined experimental setups #2 and #5 (Fig. 3) because these resulted in the highest sensitivity of received radio signals to object state change. We placed one floor-facing ceiling-mounted antenna directly above each zone (setup #2), and we also added two angled antennas to the patient-bed zone (setup #5). We used setup #5 for the patient-bed zone because most tasks that require tracking are performed in the patient-bed area.

Based on our experimental and deployment results, we propose the following rules for determining the optimal placement of RFID antennas in the trauma bay:

1. Divide the room into several zones that represent main locations of object storage and use.
2. Cover each zone with one floor-facing, ceiling-mounted antenna. If two zones are close to each other, they could be scanned by a single ceiling-mounted antenna placed in the middle of the zones.
3. Place ceiling-mounted antennas closer to the wall, or if possible, closer to metallic surfaces (e.g., metallic cabinets). This arrangement results in higher sensitivity to distance changes when objects move (e.g., location change, motion status change) because metal causes volatile readout rates.
4. In addition to the ceiling-mounted antenna covering the main area of object use (e.g., patient-bed area), add two angled antennas for improved signal detection rates.

Because the layout of resuscitation areas is similar across most trauma centers, our results and rules will be applicable to other trauma centers.

6.2. Placement of RFID tags based on object features

The placement of RFID tags on objects was guided by our analysis of object features such as size, shape, composition and purpose. This analysis was complemented by an analysis of providers' interactions with objects. The size and shape of the object surface were important parameters for selecting RFID tag types. Small and irregularly shaped surfaces posed challenges for tag placement. To manage these challenges, we used small tags or folded a larger tag around the object. These solutions, however, caused radio signal attenuation and difficulties in detecting object use. For example, of the tandem tags attached to the thermometer, the tag on the probe always performed poorly, which made it unsuitable for detecting the use of the thermometer. The use of tandem tags requires additional study to identify an effective strategy for detecting objects in use.

Object material and composition also posed challenges to reliable signal detection. Regular RFID tags attached to metallic and liquid-based objects yield no signal and are not detectable. Objects made of metal can be tagged with on-metal tags, but this is an expensive solution. To manage the problem of tagging liquid-based objects such as IV fluid bags, we placed tags on the edges of bags to minimize contact between the tag and the liquid containing portion of the bag. This solution produced reliable results. We were able to detect fluid bags in use and distinguish between different types of fluid. However, RFID tags that operated close to human body experienced performance degradation. For example, stethoscopes are carried around the neck and the contact with and occlusions by human body caused radio signal interference.

Based on our experimental and deployment results, we propose the following rules for determining the optimal placement of RFID tags on medical objects and equipment in the trauma bay:

1. *Tag type*: Select the tag type based on object material and composition. Use on-metal tags for objects that contain metallic parts. For objects filled with fluid, use regular tags but attach them along their width for improved signal detection.
2. *Number of tags and their placement*: For each object, identify surfaces that could carry a tag. Determining the most appropriate placement for tags will depend on:
   a. Surface accessibility: For sterile objects, tags should be placed on the wrapping. All other objects can be tagged directly.
   b. Shape constraints: As tag performance degrades with tag folding, surfaces with less curvature are more appropriate for tagging than those requiring the folding of a tag.
   c. Surface smoothness: Smooth surfaces are better for tagging because tags adhere better.
   d. Object-provider interaction characteristics: Identify parts of the object that are frequently in contact with human body vs. those that are rarely touched by providers. Tags should ideally be placed on parts that are less prone to contact. Placement of tags will also depend on the duration of contact with an object:
      i. Long contact: For objects characterized by long contact, attach two tags in tandem, placing one tag at the point where provider's hand or patient's body covers the tag when in use, and placing the other tag at the location where the tag remains exposed when in use.
      ii. Brief contact: For objects characterized by brief contact, tandem tagging does not apply. Still, we propose attaching two tags to the exposed parts of the object for more reliable detection. If the object is small, use only one tag to prevent tag-coupling issues.

6.3. Identifying objects in use based on location, motion and contact information

Although zone-based information, motion status, and contact modes of objects provided needed input for guiding the placement of RFID tags, these cues posed several challenges to reliable signal detection. We argued that objects located in the patient-bed zone are more likely to be in use than objects in other zones. However, we observed that inferring an object's use from its location in the area around the bed is not optimal. Objects were often brought to the patient bed long before use, or they were immediately returned to their storage place after a short use. Location-based cues were least reliable for objects that remained in the bed zone even if not in use. For example, the stethoscope (carried around the neck) is always around the bed. Another object that shows the same pattern is the trauma shears that are usually kept in pockets. To decide whether these objects are in use, we needed to include motion and contact cues.

Motion and contact cues too can be problematic for reliable detection of object use. Although stationary objects are less likely to be in use than moving objects, they may experience slight movements as well. For example, a cervical collar on the patient's neck moves along with the patient, e.g., when the patient is rolled on a side to check for back injuries. In general, patient movements are random and difficult to model, which is especially challenging with children. In this work, we focused on objects with predictable motion patterns, such as the laryngoscope or thermometer. Random human movements and occlusions pose challenges for tracking complex work processes using RFID technology. We will address these challenges in our future work.

Finally, we observed providers interacting with objects for different purposes, making the contact cue alone unreliable for task detection. In addition to the actual use, objects were held during relocation or were taken erroneously and then returned. Our analysis of the duration of different interaction types showed that it is possible to eliminate false interactions by adjusting a duration threshold, depending on the task.

6.4. Practical issues

Results from our initial deployment of RFID technology in the actual setting of the trauma bay pointed to several practical issues. First, we needed to ensure that the placement of RFID antennas is minimally obtrusive to team activities. Although the antennas were active only during simulation sessions, their placement required considering esthetics of the setting as well as possible interference with medical equipment in the room. For example, movable surgical lights are suspended from the ceiling on mechanical arms over the patient bed. These mechanical arms are often moved during patient evaluation and may collide with any objects protruding from the ceiling. Rather than suspending overhead antennas on a pole, we attached them directly to the ceiling to avoid obstructing the use of surgical lights.

Second, potential radio interference between RFID technology and medical equipment in the room is a critical issue and may cause equipment malfunctioning if not addressed. van der Togt et al. [25] found 68 instances of interference in 246 tests, ranging from minor effects (e.g., unexpected noise on the computer monitors) to potentially hazardous failures (e.g., infusion pumps and ventilators stopping). We performed basic interference tests at CNMC on the patient monitor and defibrillator when RFID antennas were both active and inactive, and found no observable interference. Clinical implementation of our RFID tracking system will require detailed testing and management of this potential issue.

Third, tagging an object was not a one-time activity and required follow-up checking of the tag status. We also needed to minimize any unintended consequences of tagging and to ensure that tags did not interfere with providers' tasks. During the deployment, we did not observe any major interference of tags with work. Tags were aligned with object shapes and tightly attached. None of the tags became loose during the experiments. Sterile objects were tagged only externally. We did, however, observe that medical personnel sometimes removed RFID tags mistaking the tags as leftovers from packaging. In addition, not all objects were tagged in our simulation studies. At this experimental stage, we only tagged objects that were used in simulation sessions. A real-world deployment of RFID technology will require tagging of all objects in the trauma bay. Our experiences showed that using RFID systems in safety–critical work settings such as trauma resuscitation require educating personnel about the system so that its functioning is reliable.

Despite the challenges and practical issues, our deployment results showed the feasibility of our approach and using passive RFID technology for detecting and tracking resuscitation objects and tasks. Our approach using passive RFID technology and the guidelines we have developed for placing RFID antennas and tags in resuscitation rooms are applicable to other work settings under following circumstances: (a) there is a need for recognizing people and activities in a highly dynamic and crowded workplace; (b) privacy is a great concern, making the visual records undesirable; (c) time and resources for special maintenance of objects that need to be tracked are limited; (d) some objects that need tracking are disposable and the cost of tracking sensors is a concern; and, (e) objects that need tracking are relatively small and hand-held during use, making the size of tracking sensors a concern. We believe that our approach is applicable to a specific domain if most or all of the above apply.

6.5. Future work

Our current research focuses on processing RFID data obtained from resuscitation events simulated in the actual trauma bay to detect objects in use and recognize team tasks and activities. We apply a machine learning-based approach, where we use one part of our dataset to train classifiers, and the other part to perform classification [37]. Considering that our dataset comes from a real-world, dynamic work environment, our results are promising for object use detection and activity recognition with passive RFID. In our future work, we will experiment with more objects and exploit inter-object relations (e.g., multiple objects used jointly to perform a task) for robust task recognition.

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