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Evaluation of real-time location systems in their hospital contexts

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ABSTRACT

Objective: The purpose of the research was to assess real-time location systems (RTLS) that have been implemented in U.S. hospitals. We examined the type of uses to which RTLS have been put, the degree of functionality of the various technologies and software, and the organizational effects of implementing RTLS.

Methods: The project was a 3-year qualitative study of 23 U.S. hospitals that had implemented RTLS for the purpose of tracking assets, personnel, and/or patients. We observed the systems in use and conducted 80 semi-structured interviews with hospital personnel and vendors. In order to protect the confidentiality of the hospitals and vendors in our sample, we conducted an aggregate analysis of our findings rather than providing evaluations of specific technologies or hospital case studies.

Results: The most important findings from our research were (1) substandard functionality of most real-time location systems in use and (2) serious obstacles to effective deployment of the systems due to the material and organizational constraints of the hospitals themselves. We found that the current best use of RTLS is for asset tracking, but importantly it requires whole-hospital deployment as well as centralized control of the system, preferably by materials management or biomedical engineering departments.

Discussion: There are serious technological, material, and organizational barriers to the implementation of RTLS, and these barriers need to be overcome if hospitals are to maximize the potential benefits of these systems.

Conclusion: In addition to considering the available technological options, hospitals must assess their unique environments, including the myriad material and organizational constraints that will affect the success of RTLS implementation.

1. Introduction

Hospital real-time location systems (RTLS) are designed to identify and locate tagged equipment, personnel, or patients as they move through hospital facilities [1,2]. Tracking equipment has the potential to allow hospitals to manage inventory better, including streamlining the process of routine preventive maintenance, thus improving the availability of needed items and reducing equipment rentals [3,4]. Tracking hospital personnel aims to document and improve clinical processes, including identifying routine breakdowns in care provision, assigning providers to patients automatically, and

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disciplining clinicians or other staff who are underperforming in their roles [5]. Tracking patients holds the promise of locating them if they get "lost" as they are moved to various departments within a hospital, verifying their identities before medical procedures, and improving discharge processes to provide quicker turnover of beds [6]. Given these varied uses of the systems, the benefits of implementing RTLS have been characterized as increasing efficiency, improving safety, and reducing operational costs [7–10].

According to a 2008 survey of U.S. hospitals, 15% of administrators indicated that their hospitals already had RTLS in place and another 43% expressed their intent to purchase a system within the next two years [11]. The largest hospital technology vendors have now entered the market with their own RTLS hardware or software. In spite of impressive industry interest, however, RTLS have had difficulty finding their niche, leaving hospitals and vendors struggling to develop uses based both on perceived needs and the evolving capabilities of the technologies themselves [12].

The current landscape of RTLS offers a variety of choices for hospitals that are interested in implementing these systems, but there is little information about the best technologies or best uses for RTLS that will justify hospitals' investment. This paper reports on the results of a 3-year qualitative study conducted at 23 U.S. hospitals. The purpose of the research was to assess the uses to which RTLS have been put, the degree of functionality of the various technologies and software, and the organizational effects of implementing RTLS. Our findings indicate that there are serious technological, material, and organizational barriers to the implementation of RTLS and that these barriers need to be overcome if hospitals are to maximize the potential benefits of these systems. In addition to reviewing the findings of our study, we provide recommendations for best practices in both decision-making about RTLS systems and in implementation and use.

2. Background

Hospital real-time location systems – also known as "indoor-positioning systems" and "real-time awareness solutions," depending on the vendor – incorporate various types of hardware with a software interface [13]. In essence, these systems work by having a hardware tag – which can be placed on a piece of equipment or a person – that communicates its location through a network of sensors that triangulates its position. The data from this network are then mediated by a software interface so that users can see a graphical representation of the location of all tags on the network or can search for a particular tag in order to locate a piece of equipment or a person [14]. The most common systems today employ radio-frequency identification (RFID), Wi-Fi or Wireless Local Area Network (WLAN), ultra-wide band (UWB), infrared (IR), ZigBee, Bluetooth, or ultrasound. Some hospitals and vendors are experimenting with implementing RTLS that use a combination of these to create hybrid networks that will more accurately track tagged items or people [15].

With such a varied range of systems to choose from, it should be no wonder that many hospitals have taken a wait-and-see approach by postponing the decision to implement a system until a "winner" emerges from the pack [16–18]. In addition to other financial concerns, one major obstacle for hospitals is the uncertainty about how RTLS will integrate with other major information technology investments, such as electronic medical record systems [19,20]. Health information technologies (HITs), however, remain mired in proprietary platforms and interfaces such that interoperability remains elusive [21].

Those hospitals that were the earliest adopters of RTLS have provided initial evidence about the real-world capabilities of the technologies and about the organizational resistance posed by reluctant staff. Initial systems – largely employing active RFID tags – suffered from extremely poor performance with inaccurate locational information and cumbersome interfaces [22]. When systems do not function well, adoption is low because users are understandably dissuaded from learning and operating a system that increases their workload [12]. As in other areas of HITs, it is important that the rollout of a system is timed so that users immediately understand its value and are motivated to learn how to use it [23]. Some of the earliest hospital RTLS are now idle or have been removed or replaced. Several early adopters also failed to explain sufficiently to hospital personnel when RTLS was used only for tracking assets, and as a result, those hospitals experienced sabotage of tags or sensors because nurses or other staff believed (falsely in these cases) that the systems were surveilling their clinical activities [24,25]. Instances like these highlight the organizational problems that can result when HITs are implemented without properly training personnel about the new systems [26].

The scholarly literature on RTLS tends to focus on the technological aspects of the systems, especially on specific case studies of pilot projects or new uses for existing systems [27–33]. Much of this research sheds important light on improving the accuracy of RTLS or on the ability of RTLS to address specific problems in particular hospital units, such as workflow or inventory management [5,34,35]. What many of these studies have in common is that the systems in question are tested or described in isolation; subsequently, there is little information about how these systems operate within holistic hospital environments or how such environments might impede or augment technical functionality [36]. For instance, one aspect of RTLS that is all but ignored in the literature is the mismatch between the initial goals of the systems and the eventual, actual functions they provide [37].

To broaden the analysis of the strengths and weaknesses of RTLS technologies, the study reported in this paper mobilizes a "sociotechnical systems" approach that situates technologies within their organizational contexts. Sociotechnical systems can be understood as complex configurations of technologies, people, and organizations, wherein technologies operate as normative (or political) structures that shape values and practices within a larger social field [38–40]. Within this framework, technologies are seen as requiring concerted social and material investments in order to be integrated smoothly into an organization, and both the successes and failures of technological implementations can be explained through attention to an array of social and organizational factors [41–44]. Through the lens of sociotechnical systems, attention is focused not only on social and technical factors as discrete variables, but instead on the interplay of these factors and their role in shaping meaning and practice in hospital settings.

3. Methods

The aim of the research was to investigate the social and organizational dimensions of identification and tracking systems in U.S. hospitals. We documented the types of RTLS hospitals use, the purpose of the systems, and their accuracy and functionality. The project was conducted between March 2007 and April 2010 with two distinct data collection periods to assess potential changes to available technologies and hospitals' experiences with RTLS. The methods for the project required site visits to hospitals that had implemented systems to identify or track patients, staff, and/or equipment. During site visits, we engaged in systematic observations of the technologies in use and conducted semi-structured interviews with personnel. The project included 23 U.S. hospitals that were selected based on their use of a qualifying system (as identified through personal contacts, press releases, or media coverage). We had a 100% response rate; every hospital we contacted agreed to participate in our study, indicating that our sample was not subject to a selection bias and could be considered broadly representative of hospitals that have implemented RTLS. Demonstrations of the systems included formal presentations made by personnel in charge of the system and informal observations of users interacting with the system. These demonstrations provided first-hand evidence of the capabilities and usability of the systems. Observations at each hospital had an average duration of three hours and ranged from two to eight hours.

In addition to informal conversations held while observing the systems, we conducted a total of 80 formal semi-structured interviews. Sixty-seven interviews were conducted with hospital staff, including 12 physicians, 6 nurses, 21 administrators, 12 information technology specialists, 7 biomedical engineers, and 9 clerical staff. The number of interviews per hospital ranged from one to eleven, with an average of three interviews per hospital site. An additional 12 interviews were conducted with vendors from seven companies that were working with these hospitals to install or maintain the systems under investigation. Finally, although the focus was on the use of the systems by hospital employees, one patient – who was included in our observations at one of the hospitals – participated in an interview.

Following widely used procedures for coding qualitative data, a multi-staged coding strategy was used whereby both investigators coded all observational notes and interview transcripts to identify core themes [45]. The different coding stages included focused discussion of the data by the investigators at the conclusion of site visits, fine-grained readings of observational notes and transcripts by each investigator, and the development of core categories and themes emerging from the data through a process of graduated selection and iteration of theoretical codes [45]. In analyzing the results, it was rare for data from observations and interviews to be contradictory. Hospital personnel were generally aware of and frank about the benefits and limitations of the RTLS in their hospitals. When a discrepancy arose, such as conflicting data between observations in hospitals and interviews with vendors, data from observations about the functionality and usability of the systems was given greater explanatory weight than claims made by vendors. The ethics boards at Arizona State University and Vanderbilt University approved this research. As dictated by the ethics review committees, the identities of the hospital sites and vendors as well as all interviewees were given confidentiality in the study, and all participants provided informed consent.

4. Results

The most important findings from our research were (1) substandard functionality of most real-time location systems in use and (2) serious obstacles to effective deployment of the systems due to material and organizational constraints of the hospitals themselves. This section will review these findings, including a description of the best uses of RTLS we observed as well as what factors enabled the most successful implementations of the technology. Because this is intended to be a review of the study's primary findings, specific quotes from informants are not provided or analyzed in this paper. Nonetheless, the findings summarized here derive directly from interview transcripts and field notes, as can be found in more specialized publications generated from this project [25,37,46]. Additionally, due to confidentiality concerns, we will not provide vendor information for the RTLS we observed. Our aim is not to evaluate products or systems on the market per se, but rather to describe how the intersection of hospital contexts and technological systems affects the performance of RTLS.

4.1. *RTLS functionality*

In spite of impressive claims from vendors about the accuracy of RTLS in tracking and locating [47], our observations of these systems in routine operation revealed that they frequently fail to deliver the precision promised. Table 1 provides an overview of each of the systems we observed. We include information on the type of technology that provided the basis for the RTLS tracking function as well as the purpose to which the RTLS had been put in the hospital. Most RTLS in our study were RFID-based, and most hospitals had implemented their systems for asset tracking. Other systems included ultrasound-, IR-, UWB-, and ZigBee-based technologies. Some hospitals were using RTLS for patient identification or tracking as well as personnel tracking, and two hospitals in our sample had added a temperature monitoring function to their system in addition to asset tracking.

The table also indicates the status of the RTLS at the time of our site visit. In most cases, the systems were operational, but in other hospitals our visit corresponded with the end of a pilot phase or the systems were already defunct. In addition, we assign a rating for the degree of accuracy or functionality of the RTLS as well as for the level of use. These low-to-high ratings are based on both our direct observations of the systems (especially for degree of accuracy) and the information provided in interviews (especially for level of use). For degree of accuracy, we assigned "low" ratings to systems in which the tag could not be found using the RTLS interface, "medium" to

Table 1 – Assessment of RTLS systems.

Hospital ID	Year of assessment	Primary technology in RTLS	Purpose of RTLS	Status of RTLS at assessment	Degree of accuracy or functionality	Level of use
01	2007	RFID	Patient ID in surgery	Defunct	Medium	NA
02	2007	A. RFID B. Ultrasound	A. Asset tracking B. Patient tracking	A. Operational B. End of pilot	A. Low B. Medium	A. Low B. Low
03	2007	RFID	Asset tracking	In development	Low	NA
04	2007	RFID	A. Asset tracking B. Personnel tracking	Operational	Medium	A. Medium B. Low
06	2007	RFID	Patient ID in ED	Operational	Low	Low
07	2007	ZigBee	Asset tracking	Pilot	Medium	Low
08	2007	RFID	Patient ID for delivering medicine	End of pilot	Low	NA
09	2007	RFID	Patient tracking	End of pilot	Medium	NA
10	2007	RFID	Asset tracking	Pilot	Low	Low
15	2007	Ultrasound	Asset tracking	Operational	Medium/high	High
16	2007	Ultrasound	A. Patient tracking B. Personnel tracking	Operational	Medium	High
11	2008	IR	A. Asset tracking B. Patient tracking C. Personnel tracking	Operational	High	A. Low B. High C. Medium
05	2009	RFID	A. Asset tracking B. Temperature monitoring	Operational	A. Medium B. High	A. Medium B. High
12	2009	RFID	Asset tracking	Operational	Low	Low
13	2009	RFID	Patient ID in surgery	End of pilot	High	Medium
14	2009	UWB	A. Asset tracking B. Patient tracking C. Personnel tracking	A. Operational B. Pilot C. Completed Pilot	Low	Low
17	2009	RFID	Personnel tracking	Operational	Medium	Medium
18	2009	RFID	Asset tracking	Operational	High	High
19	2009	RFID	A. Asset tracking B. Patient tracking	Operational	Medium	A. Low B. High
20	2009	RFID	A. Asset tracking B. Temperature monitoring	Defunct	A. Medium B. High	NA
21	2009	RFID	Asset tracking	End of pilot	Medium	Low
22	2009	ZigBee	Asset tracking	Operational	High	High
23	2009	RFID	Asset tracking	End of pilot	Low	Low

indicate systems that helped users home in on a broad hospital area where the tag was located, and “high” to designate systems that had room-level accuracy. In our rating of level of use, “low” means either that few tags were tracked on the system or that personnel were not accessing the system to find tags, “medium” communicates that personnel were using the systems to find some tags at least some of the time, and “high” indicates both that many tags were actively tracked on the system and personnel were regularly accessing the software interface to find those tags. In the majority of cases, the interview data supported our observations of the systems. For a few hospitals, vendors or hospital personnel claimed that the degree of accuracy was better than that found in our observations, so in those instances we placed greater emphasis on our observations. Thus, Table 1 provides a summary of our sample of hospitals and RTLS as well as our findings. Not surprisingly, in the majority of cases, poor performance of the RTLS was also tied to very low use.

Notably, the earliest generation RTLS we observed performed poorly during demonstrations. Some tagged items were simply not found, and others were registering in the wrong locations, including spaces “off the map,” so to speak, such as an IV pump that was shown as hovering outside of the fourth floor of the hospital. In some cases, hospital personnel reported that the RTLS provided such poor locational information that the system increased the time to procure needed equipment. In other words, their informal, non-technological system of findings items was deemed superior to RTLS. One common negative feature of these RTLS installations was the short battery life of tags. Even though many vendors had included functions that could send alerts to users to warn of low batteries, many users either ignored these warnings or could not find the item in time to change the battery before the tag went dark. In one instance, a hospital administrator complained that the vendor had fitted its first-generation tags with batteries that were not available on the U.S. market, which made the hospital dependent on the vendor to maintain its supply. In interviews, many hospital personnel attributed the failure of early RTLS either to the adoption of immature technology or the inability of RFID to perform well in a hospital context.

Newer RTLS offer technological improvements but systems have maintained former or acquired novel drawbacks. The biggest improvement with RTLS appears to be in the implementation of new systems. Many are now able to operate on existing wired or wireless networks in hospitals, and some vendors offer “plug-and-play” technologies that are relatively easy to install. This means it is both faster and less expensive to have systems go live. Newer RTLS also offer improved tracking capabilities, yet most of the systems continue to fail at accomplishing room-level accuracy. Depending on the specific purposes of the locational system deployed by a hospital, the technological improvements have made RTLS more user-friendly. In non-urgent situations, searching for an item within a smaller zone of the hospital can make equipment much easier to find, and improved accuracy leads to better results finding people who are tagged as well. In spite of these gains, the benefits of RTLS continued to fail to impress clinical staff in our sample, but personnel in biomedical engineering and materials management departments hailed these technologies as major improvements to their work practices.

As RTLS technologies improve, many vendors are adding innovative functions to the software interfaces, which can create new problems. For instance, through "dynamic associations" some systems link tracking data to hospital billing systems so that when certain personnel or pieces of equipment are registered by the systems as being in contact with a patient, the patient can be automatically invoiced for those services. As reported by hospital staff who have worked with these software applications, these functions can lead to both false positives and false negatives, so that the automated system does not reduce workload (because everything needs to be recorded manually anyhow) and can actually increase workload (because staff need to correct errors that the system generates). In addition, there are challenges with tagging patients, including the development of reusable tags that can be sterilized or alternately low-cost disposable tags [25]. RTLS systems have improved since their introduction in health care, but the technological limitations are just one element of making RTLS function well in hospitals.

4.2. *Material and organizational constraints on RTLS operability*

Hospitals have complex material spaces and organizational cultures that affect RTLS. Hospitals are not standardized places from their buildings and campuses to the organization of their personnel. These differences present major challenges for RTLS; even when vendors have had successes in one hospital, they often cannot replicate those outcomes in another. In this section, we analyze the findings from our observations and interviews using a sociotechnical-systems approach to evaluate RTLS in the specific contexts in which they are deployed.

Hospitals are often combinations of buildings, sometimes dating from very different time periods [48]. Indeed some of the hospitals in our study consisted of buildings that were over 100 years old. This means that building materials may differ between structures, even for the same hospital, which can present problems for accurately triangulating tags when signal strength is affected. Lead-shielded rooms create challenges for RTLS to operate within those spaces as well as in contiguous hallways and rooms. Access to an electrical supply and the ability to pull cables can also create problems with RTLS installations because the systems depend on strategically placed receivers that will "read" the signals emitted by tags. Newer facilities frequently have interstitial spaces above the ceiling that can be accessed for cable and electrical drops, but these modifications are expensive, difficult, or impossible in older buildings.

The layout of hospitals can also interfere with RTLS installations. Hospitals can have confusing floor plans, especially where buildings intersect with each other. While personnel adapt to these spaces quickly, the flow of people and equipment through these spaces may not be standardized. Ad hoc patterns of flow impede effective implementation of RTLS because the installers must make decisions about the placement of receivers based on their assumptions about the direction of movement through hallways as well as presumptions about the use of elevators and stairways. Hospital personnel that we interviewed had many stories about the surprising points of passage through their facilities that they found *after* they had implemented RTLS and were troubleshooting to improve their tracking results.

In addition to the constraints that hospitals' buildings impose on RTLS functionality, we observed that hospitals are also incredibly porous places. Equipment is especially prone to disappear from hospital facilities. Small items, such as telemetry devices, can get lost in patients' bedding and end up damaged or thrown away. Theft can be a factor as well with hospitals reporting wheelchair loss as a major contribution to equipment costs. RTLS are designed to solve these problems so that items will not be unknowingly lost or stolen. The ability of RTLS to do so, however, is attenuated by more routine reasons why equipment leaves hospital facilities. For instance, wheelchairs exit hospitals in order to help patients to waiting vehicles at discharge, and RTLS cannot distinguish between these cases and theft to prevent the latter. Similarly, some equipment, such as IV infusion pumps, will remain with patients when they are transferred to other facilities (such as long-term acute care facilities or hospice). This means that alerts to personnel that wheelchairs or other highly mobile equipment have left the building are bound to be ignored because these events are frequent and because personnel come to assume that the occurrences are legitimate.

Beyond the material differences between hospitals, there are organizational differences that make an impact on how RTLS is deployed and how effective it can be. In our sample, the majority of hospitals we visited exhibited territorial cultures in which departments are atomized and have their own budgets, control their own technology decisions, and assign their own workflow and responsibilities to personnel. This made agreement and coordination among departments difficult, especially for systems that lose effectiveness if not implemented universally.

A related problem is that most decisions about RTLS are made in ad hoc ways without clear clinical goals. This was true for most department-level and hospital-wide deployments. In some hospitals, we found that the decision to purchase RTLS was motivated by the perception that it was necessary simply because it was cutting edge. In these cases, we observed that there was a poor understanding of how RTLS was to be maintained and used, and by whom. For example, RTLS had been implemented in one hospital for asset tracking, but the administrators who had backed the project had never defined who would be responsible for tagging items, entering the information into the database, and searching for and retrieving equipment as needed. It should be little surprise that there were few tags on the network and little awareness of the RTLS overall by hospital personnel. In other instances of top-down deployment of RTLS, we noted that administrators failed to get buy-in from personnel, so there was significant sabotage of the system or the technology had simply been rendered defunct. With personnel tracking in particular, our interviews revealed that hospital staff refused to wear tags in one hospital and they damaged or hid tags in another. Thus, the organizational culture can be a major impediment to RTLS "working" in a hospital context.

4.3. *Emerging "winner" and "loser" in RTLS operations*

With so many obstacles to the effective use of RTLS in hospitals, it is difficult to portray any single deployment we observed as a model for other hospitals. Taken together, however, our sample of hospitals indicates that asset tracking is the clear best purpose to which RTLS has been put. In order to maximize their utility, however, RTLS must be implemented throughout hospital facilities so that tracking coverage is as complete as possible, and hospitals must choose vendors that can guarantee a fair level of accuracy in their tracking systems. Another critical element to making RTLS a success is placing the systems within the domain of a department that is responsible for hospital equipment, such as materials management or biomedical engineering. In our sample, these departments had the most stake in making RTLS function well, and they were in the best position to make use of the tracking function for inventory control or preventive maintenance. To minimize sabotage of equipment tags, clinical staff need to be educated about the tracking system and permitted to access it should they find it valuable, but they should not be required to use it. In our study, the hospitals that assigned personnel from materials management to locate and deliver equipment to clinicians achieved higher rates of use of their RTLS as well as greater satisfaction among all personnel.

The use of RTLS with the worst results is the tracking of people. Not only do these systems foster so much resistance from hospital staff that they could jeopardize the entire RTLS implementation (including asset tracking), but also the reasons for tracking personnel are unconvincing. Specifically, in our sample, none of the hospitals that attempted to track personnel had any clear goals for doing so. Without a strong rationale of improving workflow or providing other clinical benefits, the utilization of RTLS for personnel tracking simply does not justify the surveillance or potential invasion of privacy of personnel, whether they are clinical or non-clinical staff. Similarly, patient tracking had limited functionality weighed against infection and cost concerns; it also introduced a by proxy form of performance monitoring of hospital staff that posed threats to worker morale [25].

5. Discussion

It is revealing that during the majority of our observations of RTLS in hospitals, administrators, clinicians, and non-clinical staff pressed us for details about other hospitals' experiences with tracking technologies. They were primarily interested in finding out how other hospitals are able to leverage their RTLS for the most accurate tracking, the best software functionality, and the elusive "hard ROI," a monetary return on investment. In essence, this illustrates the collective disappointment that many hospitals have experienced with RTLS. The technological capabilities of these systems – though improving – continue to underperform in hospital contexts.

Context matters, of course, and hospitals are challenging environments for new information technologies [36]. Even if the technology itself were perfected, a sociotechnical-systems approach underscores that the material environment of hospitals impedes the effective deployment of RTLS due to the non-standardized design of buildings and the complex flow of people and equipment. The organizational cultures of hospitals present their own problems due, on one hand, to the territoriality of departments limiting the scope of the deployment and, on the other, to poor divisions of labor surrounding the use of RTLS and the mistrust of personnel. These contextual factors must be evaluated as hospitals make choices about the implementation of RTLS.

Naturally, our study has limitations. First, some of the systems we observed were first generation systems that are now obsolete. One would expect poorer performance from these RTLS, and indeed, this is what we found. Nonetheless, the material and organizational constraints apply to the oldest and newest technologies, so this underscores the importance of these factors in the successful use of RTLS. In other words, technology may be changing fast, but hospitals are not. Second, we included a limited number of hospitals in our sample (about two dozen) because of the intensive, observational design of the study. We included hospitals with as diverse a range of tracking technologies as possible in order to have the most exposure to systems currently being sold and implemented. Given our need to protect the confidentiality of the hospitals and vendors that participated in our study, we cannot provide specific information about the current technologies on the market, so our recommendations are based on our aggregate findings about which systems performed best in our sample. Future studies are needed to measure the extent to which specific RTLS vendors are addressing the challenges that hospital contexts pose.

6. Conclusion

Gains have been made with RTLS technology, yet even should vendors further improve the accuracy of their systems' tracking functions and software capabilities, there will remain obstacles for RTLS to operate seamlessly and with clear purposes in hospitals. Hospitals have a host of material and organizational constraints that affect the performance of new information technologies [12,49]. Hospitals tend to consist of old buildings that are often arranged in complex, unintuitive configurations. Hospitals are also porous places because care extends beyond the confines of these facilities. And hospitals are made up of departments and units with hierarchies of personnel who can be territorial about their resources. Implementation of RTLS must go beyond the simple deployment of technology to be effective [26,50]. In advance of selecting a tracking technology, plans need to be designed that will detail what goals RTLS will meet, who will manage and operate the system, and how buy-in will be obtained from personnel [51]. Hospitals should choose the RTLS that best matches

Summary points

What was known before the study?

- Hospitals have been investing in real-time location systems (RTLS) to track assets, patients, and staff.
- The benefits of implementing RTLS have been characterized as increasing efficiency, improving safety, and reducing operational costs.

What the study has added to the body of knowledge?

- The technological capabilities of RTLS – though improving – continue to underperform in hospital contexts.
- The specific context of each hospital must be evaluated as administrators make choices about the implementation of RTLS. Specifically, in regard to:
  - The material environment of hospitals, which can impede the effective deployment of RTLS due to the non-standardized design of buildings and the complex flow of people and equipment.
  - The organizational cultures of hospitals, which present their problems due to (1) the territoriality of departments limiting the scope of the deployment and (2) poor divisions of labor surrounding the use of RTLS and the mistrust of personnel.
- With important caveats detailed in the paper, our sample of hospitals indicated that asset tracking is currently the "best-use" for RTLS, and the worst results of RTLS were linked to hospital implementations that tracked patients and staff.

their specific goals and will provide the best results in their own facilities, given their unique material and organizational constraints. The majority of hospitals in our sample did not anticipate the extent to which it was necessary to consider the specific demands of their facilities during RTLS selection and implementation. Perceiving RTLS as an off-the-shelf technology may serve vendors' goals but it undermines successful deployment. By prioritizing hospital context, however, RTLS can perhaps be leveraged to better serve the system of health care.

Author contributions

The authors contributed equally to the design of the study, the collection and analysis of the data, and the writing of this manuscript.

Competing interests

There is no conflict of interest.

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REFERENCES

[1] S. Davis, Tagging along: RFID helps hospitals track assets and people, Health Facil. Manage. 17 (12) (2004) 20–30.
[2] A.-M. Vilamovska, E. Hatziandreu, H.R. Schindler, C. van Oranje-Nassau, H. de Vries, J. Krapels, Study on the Requirements and Options for RFID Application in Healthcare. Identifying Areas for Radio Frequency Identification Deployment in Healthcare Delivery: A Review of Relevant Literature, RAND Corporation, Santa Monica, CA, 2009.
[3] M. Glabman, Room for tracking: RFID technology finds the way, Mater. Manage. Health Care 13 (5) (2004), 26–28, 31–34, 36.
[4] G. Calvaneso, Where's your equipment when you need it? Health Manage. Technol. 20 (10) (1999) 20–30.
[5] P.H. Frisch, P. Booth, S. Miodownik, Beyond inventory control: understanding RFID and its applications, Biomed. Instrum. Technol. 2010 (2010) 39–40.
[6] I.C. Chang, L. Cheng-Yaw, L. Yu-Chuan, C. Chia-Cheng, L. Chien-Tsai, C. Chieh-Feng, et al., Pervasive observation medicine: the application of RFID to improve patient safety in observation unit of hospital emergency department, in: R. Engelbrecht, A. Geissbuhler, C. Lovis, G. Mihalas (Eds.), Connecting Medical Informatics and Bio-informatics: Proceedings of MIE 2005, IOS Press, 2005, pp. 311–320.
[7] L. Revere, K. Black, F. Zalila, RFIDs can improve the patient care supply chain, Hosp. Top. 88 (1) (2010) 26–30.
[8] C. Thuemmler, W. Buchanan, A.H. Fekri, A. Lawson, Radio frequency identification (RFID) in pervasive healthcare, Int. J. Healthc. Technol. Manage. 10 (1–2) (2009) 119–120.
[9] Y.Z. Mehrjerdi, Radio frequency identification: the big role player in health care management, J. Health Organ. Manage. 25 (5) (2011) 490–505.
[10] A.M. Wicks, J.K. Visich, S. Li, Radio frequency identification applications in healthcare, Int. J. Healthc. Technol. Manage. 7 (6) (2006) 522–530.
[11] HIMSS (Healthcare Information and Management Systems Society), 19th Annual – 2008 HIMSS Leadership Survey. Final Report: Healthcare CIO, Chicago, 2008.
[12] J.A. Fisher, T. Monahan, Tracking the social dimensions of RFID systems in hospitals, Int. J. Med. Inform. 77 (3) (2008) 176–180.
[13] RFID Network, RTLS Market Overview, RFID Network, 2010.
[14] V.N. Carrasco, S.S. Jackson, Real time location systems and asset tracking: new horizons for hospitals, Biomed. Instrum. Technol. 44 (4) (2010) 318–320.
[15] R. Krohn, The optimal RTLS solution for hospitals: breaking through a complex environment, J. Healthc. Inf. Manage. 22 (4) (2008) 14–20.
[16] B.K. Schuerenberg, Keeping tabs with RFID, Health Data Manage. 13 (10) (2005) 39–40, 42, 44.
[17] J. Degaspari, Keeping track: barcodes and RFID tags make inroads in hospitals, Healthc. Inform. 28 (3) (2011) 44–50.
[18] E. McGrady, S. Conger, S. Blanke, B.J.L. Landry, Emerging technologies in healthcare: navigating risks, evaluating rewards, J. Healthc. Manage. 55 (5) (2010) 353–360.

[19] M. Bouet, G. Pujolle, RFID in ehealth systems: applications, challenges, and perspectives, Ann. Telecommun. 65 (9) (2010) 497–500.
[20] Y.-C. Chung, P.-C. Shih, K.-C. Li, C.-T. Yang, C.-H. Hsu, F.-R. Hsu, et al., in: H. Takeda (Ed.), Medicare-grid: New Trends on the Development of E-health System based on Grid Technology, E-health: Springer, Boston, 2010, pp. 148–150.
[21] R.A. Perrin, N. Simpson, RFID and bar codes: critical importance in enhancing safe patient care, J. Healthc. Inf. Manage. 18 (4) (2004) 33–40.
[22] J. Raper, G. Gartner, H. Karimi, C. Rizos, A critical evaluation of location based services and their potential, J. Location Based Serv. 1 (1) (2007) 5–45.
[23] S. Kumar, G. Livermont, G. McKewan, Stage implementation of RFID in hospitals, Technol. Health Care 18 (1) (2010) 31–40.
[24] J.A. Fisher, Indoor positioning and digital management: emerging surveillance regimes in hospitals, in: T. Monahan (Ed.), Surveillance and Security: Technological Politics and Power in Everyday Life, Routledge, New York, 2006, pp. 77–80.
[25] T. Monahan, J.A. Fisher, Surveillance impediments: recognizing obduracy with the deployment of hospital information systems, Surveill. Soc. 9 (1–2) (2011) 1–16.
[26] N.M. Lorenzi, L.L. Novak, J.B. Weiss, C.S. Gadd, K.M. Unertl, Crossing the implementation chasm: a proposal for bold action, J. Am. Med. Inform. Assoc. 15 (3) (2008) 290–300.
[27] T. Ostbye, D.F. Lobach, D. Cheesborough, A.M.M. Lee, K.M. Krause, V. Hasselblad, et al., Evaluation of an infrared/radiofrequency equipment-tracking system in a tertiary care hospital, J. Med. Syst. 27 (4) (2003) 367–370.
[28] B. Christe, R. Rogers, E. Cooney, Analysis of the impact of a radiofrequency identification asset-tracking system in the healthcare setting, J. Clin. Eng. 35 (1) (2010) 49–50, http://dx.doi.org/10.1097/JCE.1090b1013e3181cf1094.
[29] S. Ting, S. Kwok, A. Tsang, W. Lee, Critical elements and lessons learnt from the implementation of an RFID-enabled healthcare management system in a medical organization, J. Med. Syst. 35 (4) (2011) 657–660.
[30] D.W. Curtis, E.J. Pino, J.M. Bailey, E.I. Shih, J. Waterman, S.A. Vinterbo, et al., SMART—an integrated wireless system for monitoring unattended patients, J. Am. Med. Inform. Assoc. 15 (1) (2008) 44–50.
[31] W. Yao, C.H. Chu, Z. Li, Leveraging complex event processing for smart hospitals using RFID, J. Netw. Comput. Appl. 34 (3) (2011) 799–800.
[32] J. Kannry, S. Emro, M. Blount, M. Ebling, Small-scale testing of RFID in a hospital setting: RFID as bed trigger, in: Proceedings of the American Medical Informatics Association Annual Symposium (AMIA'07), 2007, pp. 384–390.
[33] S.H. Chew, P.A. Chong, E. Gunawan, K.W. Goh, Y. Kim, C.B. Soh, A hybrid mobile-based patient location tracking system for personal healthcare applications, in: Engineering in Medicine and Biology Society, 2006. EMBS'06. 28th Annual International Conference of the IEEE, August 30 2006–September 3 2006, 2006, pp. 5188–5190.
[34] J. Stahl, J. Holt, N. Gagliano, Understanding performance and behavior of tightly coupled outpatient systems using RFID: initial experience, J. Med. Syst. 35 (3) (2011) 291–300.
[35] K. Zheng, H.M. Haftel, R.B. Hirschl, M. O'Reilly, D.A. Hanauer, Quantifying the impact of health IT implementations on clinical workflow: a new methodological perspective, J. Am. Med. Inform. Assoc. 17 (4) (2010) 454–460.
[36] M.I. Harrison, R. Koppel, S. Bar-Lev, Unintended consequences of information technologies in health care: an interactive sociotechnical analysis, J. Am. Med. Inform. Assoc. 14 (5) (2007) 542–550.
[37] J.A. Fisher, T. Monahan, The "biosecuritization" of healthcare delivery: examples of post-9/11 technological imperatives, Soc. Sci. Med. 72 (4) (2011) 545–550.
[38] M. Akrich, The de-scription of technological objects, in: W.E. Bijker, J. Law (Eds.), Shaping Technology/Building Society: Studies in Sociotechnical Change, The MIT Press, Cambridge, MA, 1992.
[39] L. Winner, The Whale and the Reactor: A Search for Limits in an Age of High Technology, University of Chicago Press, Chicago, 1986.
[40] T.P. Hughes, The evolution of large technological systems, in: W.E. Bijker, T.P. Hughes, T. Pinch (Eds.), The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology, The MIT Press, Cambridge, Massachusetts, 1987.
[41] G.C. Bowker, S.L. Star, Sorting Things Out: Classification and its Consequences, MIT Press, Cambridge, MA, 1999.
[42] W.E. Bijker, J. Law, Shaping Technology/Building Society: Studies in Sociotechnical Change, MIT Press, Cambridge, MA, 1992.
[43] T. Monahan, Globalization, Technological Change, and Public Education, Routledge, New York, 2005.
[44] N. Oudshoorn, Diagnosis at a distance: the invisible work of patients and healthcare professionals in cardiac telemonitoring technology, Sociol. Health Illn. 30 (2) (2008) 272–280.
[45] K. Charmaz, Constructing Grounded Theory, Sage, London, 2006.
[46] T. Monahan, J.A. Fisher, Implanting inequality: empirical evidence of social and ethical risks of implantable radio-frequency identification (RFID) devices, Int. J. Technol. Assess. Health Care 26 (4) (2010) 370–380.
[47] C. Gearon, Behind the hype, Hosp. Health Netw. 79 (6) (2005) 22–30.
[48] A. Adams, Medicine by Design: The Architect and the Modern Hospital, 1893–1943, University of Minnesota Press, Minneapolis, 2007.
[49] K.W. Goodman, E.S. Berner, M.A. Dente, B. Kaplan, R. Koppel, D. Rucker, et al., Challenges in ethics, safety, best practices, and oversight regarding HIT vendors, their customers, and patients: a report of an AMIA special task force, J. Am. Med. Inform. Assoc. 18 (1) (2011) 77–80.
[50] D. Murphy, Is RFID right for your organization? Mater. Manag. Health Care 15 (6) (2006) 28–30.
[51] A. Dash, Lost + found: making the right choice in equipment location systems, Health Facil. Manage. 22 (11) (2009) 19–20.