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Review

Review

Real-time locating systems to improve healthcare delivery: A systematic review

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ABSTRACT

Objective: Modern health care requires patients, staff, and equipment to navigate complex environments to deliver quality care efficiently. Real-time locating systems (RTLS) are local tracking systems that identify the physical locations of personnel and equipment in real time. Applications and analytic strategies to utilize RTLS-produced data are still under development. The objectives of this systematic review were to describe and analyze the key features of RTLS applications and demonstrate their potential to improve care delivery.
Materials and Methods: We searched MEDLINE, SCOPUS, and IEEE following PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. Inclusion criteria were articles that utilize RTLS to evaluate or influence workflow in a healthcare setting. We summarized aspects of relevant articles, identified key themes in the challenges of applying RTLS to workflow improvement, and thematically reviewed the state of quantitative analytic methodologies.
Results: We included 42 articles in the final qualitative synthesis. The most frequent study design was observational (n = 24), followed by descriptive (n = 12) and experimental (n = 6). The most common clinical environment for study was the emergency department (n = 12), followed by entire hospital (n = 7) and surgical ward (n = 6).
Discussion: The focus of studies changed over time from early experience to optimization to evaluation of an established system. Common narrative themes highlighted lessons learned regarding evaluation, implementation, and information visibility. Few studies have developed quantitative techniques to effectively analyze RTLS data.
Conclusions: RTLS is a useful and effective adjunct methodology in process and quality improvement, workflow analysis, and patient safety. Future directions should focus on developing enhanced analysis to meaningfully interpret RTLS data.

Key words: "real-time locating system," RTLS, workflow, systematic review

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INTRODUCTION

Background and significance

Modern healthcare delivery systems span complex environments across multiple physical locations. For health systems to function optimally, patients, staff and equipment must effectively navigate these environments.[1] Purposeful movement of each stakeholder within these environments may contribute to efficient healthcare delivery.[2] Impediments to effective movement can result in delays, waste and higher cost.[3] There has been much interest in the application of tracking technologies in health care to improve the effectiveness, safety, and value of care delivery.[4–6]

Real-time locating systems (RTLS) are local systems to identify and track the physical location of objects or people in real time. RTLS location information is generated from the interaction of locating tags attached to the persons or objects and sensors strategically placed throughout the environment of interest. This information is displayed to clinical workers in real time and available to analysts for post hoc analysis. A range of software applications exist to integrate the data and interface with various operational systems.[7] These RTLS applications have great potential to improve patient tracking, asset management, patient flow, patient-staff interactions, building design, and emergency management.[8,9]

Health systems have attempted to implement RTLS to streamline the availability of needed equipment, track hospital personnel to improve clinical processes, and find patients easily as they move through the care environment.[10–13] These efforts are based on the principles of scientific management, largely attributed to Frederick Taylor, to improve processes using logic, rationality, elimination of waste, and standardization. Taylor's time and motion studies break down a process into its constituent elements and motions to find the "one best way."[14] In this historical context, RTLS can be considered an advanced tool with which one can perform such studies. However, challenges to effective implementation and analysis include substandard functionality and difficulty integrating RTLS into the organizational processes of each hospital.[15] While some studies have shown difficulty gleaning meaningful conclusions from RTLS-derived data in busy clinic,[16–18] others have developed innovative solutions to overcome typical barriers (high-traffic areas, equipment failure, data analysis, and filtration) and facilitate successful RTLS applications. For example, some studies have shown difficulty gleaning meaningful conclusions from RTLS-derived data in busy clinics to enhance throughput. Berg et al[19] strategically paired historical observations with RTLS data, and then used probabilistic modelling to successfully optimize clinician scheduling in an outpatient clinic. Alternatively, Conley et al[20] created a novel RTLS-based metric ("face time") to successfully improve descriptions of clinic performance. These examples highlight innovative solutions to overcome typical barriers (high-traffic areas, equipment failure, data analysis, and filtration) and facilitate successful RTLS applications.

Additionally, for RTLS to have a substantial impact on operational optimization in complex hospital environments, robust analysis must be conducted to identify unit and hospital-level roadblocks, track trends over time, and augment improvement efforts. While RTLS has been shown to improve clinical operations in limited applications, the key features of useful RLTS deployment to improve clinical workflow and operations have not been examined. Furthermore, the analytic methodologies to produce useful conclusions from RTLS-derived data have not been systematically reviewed.

OBJECTIVE

The objective of this article is to perform a systematic review of existing applications of RTLS to augment healthcare improvement efforts. We searched for studies in which RTLS was applied to clinical scenarios for process improvement. We examined the key features of successful RTLS deployment, the types of clinical outcomes tracked, and the analysis methods used to draw conclusions.

MATERIALS AND METHODS

Search strategy

We conducted a systematic literature review of RTLS-related articles written in English and published from 1979 to 2019. We searched Ovid Medline, IEEE, and Scopus to include articles encompassing a broad range of medical, social sciences, and technical topics. The search terms were constructed to use controlled keywords to broadly identify RTLS applications in pertinent healthcare areas. We included radio-frequency identification (RFID) in our search because it is the most common communication method used in RTLS, and its abbreviation is frequently used interchangeably with RTLS.

1. Real time locat* OR Real-time locat* OR Radio-frequency identification OR Radiofrequency identification OR Location track* OR Location-track* OR RFID OR RTLS
2. Workflow OR Clinical OR Surgery OR Patient OR Emergency OR Healthcare
3. 1 AND 2

The search was conducted on May 1, 2019. All titles were independently reviewed for inclusion by 2 trained reviewers (C.T.X., S.S.B.). If both reviewers selected a title for inclusion, the full text was reviewed. This article inclusion process followed PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines.[21] The agreement and interrater reliability were calculated using Cohen's kappa.[22]

Inclusion and exclusion criteria

We sought to identify articles specifically related to RTLS use in process improvement and measuring workflow in a healthcare setting while maintaining a wide enough scope to capture all relevant publications. Inclusion criteria for publications were articles that (1) utilized a RTLS or equivalent technology to evaluate or influence workflow in a healthcare setting, (2) included the full text, and (3) were written in English. Publications describing studies in any of the following areas were excluded: (1) primary use of technology not typical to standard RTLS, such as mobile phones; (2) use of RTLS outside of a healthcare setting; (3) lack of application of RTLS to workflow; (4) sole evaluation of ethical implications of RTLS; or (5) narrow tracking of specific equipment for a limited surgical or laboratory process. We also excluded letters to the editor, commentaries, systematic reviews, and editorials.

Abstraction process

Three team members performed the information extraction from the included articles. Abstracted information included the following attributes: (1) study design, (2) country of origin, (3) year published, (4) participant information, (5) purpose and description of RTLS technology used, (6) control group (if applicable), (7) variables or outcomes of interest and how they were assessed, (8) data collection procedures, (9) summary measures used, (10) results, (11) discussion, and (12) limitations. Key conclusions, lessons learned, and future directions were abstracted from discussion sections. These attributes were based on modified PRISMA requirements.[21]

Data analysis

We conducted 2 types of data analysis. First, we generated a statistical summary to characterize all studies based on their location, clinical setting, year of publication, and study design. Study designs were categorized into 3 categories: descriptive, observational, and experimental.[23] Descriptive studies were subcategorized into studies that focused on either the feasibility of implementation of RTLS in a clinical environment or the acceptability of RTLS by clinical staff.[24] Observational studies were studies in which the authors did not manipulate the study environment by directly intervening or controlling for confounding factors. These studies used RTLS technology to track the movements of clinicians or patients through their normal routine. Observational studies also included case studies. Experimental studies were studies in which researchers actively performed an intervention that used RTLS either as the intervention itself, or as a tool to collect workflow data to provide insight into other variables, such as patient wait times. These studies were conducted in controlled environments.

The studies that were categorized as observational were further separated into 3 categories based on the study type: cross-sectional, cohort, or case controlled.[25] Studies with a cross-sectional study type were studies that collected a sample from the population and analyzed data from different groups to make comparisons. Cohort studies were studies that followed a specific group over a period of time. Studies with a case-controlled study type retrospectively compared groups that differed in their conditions or outcomes to determine a correlation.

Owing to the heterogeneity of the included studies, the second type of analysis included a narrative synthesis to extract themes from the data. Narrative synthesis is an approach that focuses primarily on textual data to summarize and explain the findings of the synthesis.[26] We determined that this was the most appropriate method to use because other quantitative meta-analysis methods were not feasible due to the heterogeneity of the included studies. Three reviewers categorized the methods, outcomes, and findings of included studies into themes. Disagreements were resolved via discussion. The first component of the narrative review was to synthesize the key "lessons learned" into themes (technology evaluation, RFID/RTLS implementation, information visibility/accuracy, staff-centered workflow evaluation, and patient-centered workflow evaluation) to create a rich description of the state of current knowledge. We created these themes by extracting lessons learned from the discussion sections, whether they were explicitly listed or implicitly discussed. We then coded the text of according to meaning and content, translated concepts from each study, and generated analytical themes.[27]

The final component of the narrative synthesis includes textual descriptions, groupings, and qualitative case descriptions of RTLS workflow analysis methods over time and challenges in RTLS research.[26] We describe key factors that explain any differences in the facilitators or barriers to successful implementation across included studies. We describe application areas such as nosocomial infections, clinic wait times, and physical space usage. We also describe challenges and solutions in the implementation of RTLS, the contextualization of RTLS data, and analytic innovations.

RESULTS

Literature search results

A total of 1886 of unique articles were retrieved from the 3 databases (Figure 1). Articles were first screened by title and abstract, and the remaining articles were examined using the full text. A total of 90 full texts were assessed for eligibility, and 33 of them were included. References of the 33 articles were scanned and evaluated, identifying 9 more articles to be included, resulting in a total of 42 articles. Of the 1796 excluded articles, a majority (n = 1579) were excluded because they were articles not using RTLS technology to evaluate or influence in-hospital workflow systems. Other major reasons for exclusion included "does not use RTLS to evaluate in-hospital workflow" (n = 56) and "articles describing, using or evaluating technology which differs fundamentally from RTLS" (n = 57). A list of all included articles and pertinent characteristics is included in the Supplementary Appendix.

Characteristics of included studies

Table 1 summarizes the included articles. Most of the articles were published in North America (n = 24, 57%) and Asia (n = 13, 31%). Two-thirds of the articles were published between 2008 and 2015 (n = 27, 64%). Slightly more than half of the included articles had an observational study design (n = 24, 57%), followed by descriptive study design (n = 12, 29%). Nearly half of the descriptive studies (n = 5) included elements of both subcategories: feasibility and acceptance. Of all of the included studies, the most common clinical setting in which RTLS was implemented was the emergency department (n = 12), followed by the entire hospital (n = 7) and the surgical ward (n = 6).

Table 2 shows the characteristics of the observational studies (n = 24). The most common clinical setting was the emergency department (n = 5) and entire hospital (n = 5), followed by the surgical ward (n = 3).

Narrative synthesis themes

The narrative synthesis generated 3 categories of study stage (early experience, optimization, and established system), with a majority of the articles focusing on the use of RTLS data in an established system (n = 21) and optimization (n = 12). Combining the study stage with the publication years, the results in Figure 2 show that the included articles from 2004 to 2006 primarily were discussing RTLS use in its early stages, focusing on feasibility and implementation. Interestingly, the focus of the articles published in later years shifted from early experiences of RTLS to ways to optimize RTLS use and the experiences of established RTLS use and its efficacy in measuring hospital workflow.

Lessons learned

Of the 42 included articles, 5 overarching themes were identified: (1) technology evaluation, (2) RFID or RTLS implementation, (3) information visibility or accuracy, (4) staff-centered workflow evaluation, and (5) patient-centered workflow evaluation. They were each assigned favorable and unfavorable subtitles based on the lessons learned, resulting in ten possible categories that the articles could be sorted into. Table 3 shows the 5 themes and the top categories. Each theme and its frequent categories are described in the following sections.

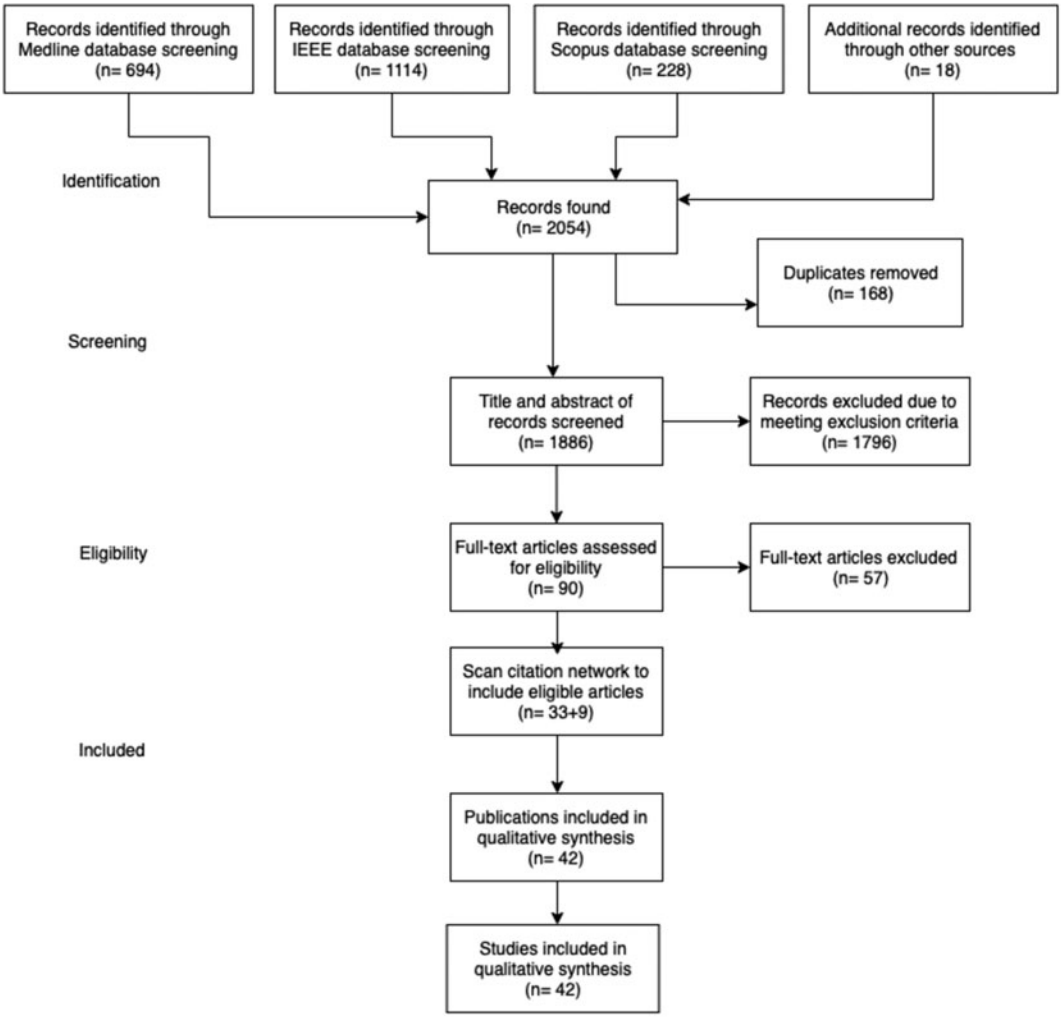

Figure 1. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) diagram of included studies.

Table 1. Summary of the included RTLS articles (n = 42)

		n	%
Study location	North America	24	57.14
	Asia	13	30.95
	Europe	5	11.91
Year published	2004-2007	5	11.91
	2008-2011	14	33.33
	2012-2015	13	30.95
	2016-2019	10	23.81
Study design	Experimental	6	14.29
	Observational	24	57.14
	Descriptive	12	28.57
	Feasibility	5	11.90
	Acceptance	2	4.76
	Both	5	11.90
Clinical setting	Emergency department	12	28.57
	Entire hospital	7	16.67
	Surgical ward	6	14.28
	Other	17	40.48

RTLS: real-time locating systems.

Technology evaluation

This theme addresses how effective the technology is in performing tasks, gives an overall evaluation of its components, and how well it integrates with other devices or systems. Fifteen articles discussed RTLS or RFID technology. Nine such articles noted the benefits, including efficient data capture with a wide variety of motion capture capabilities, not interfering with other medical equipment, and convenient features that help improve patient comfort and reduce care provider workflow.[19,28–35] For example, Stahl et al[36] found that RTLS was also found to be effective in approximating patient wait times and patient-provider face time using collected location data in an outpatient setting. Five other articles noted areas for improvement, which included that the technology was not always as effective or as cooperative as imagined and that it performed better in simulated environments in which there were less variables and unpredictability at play.[6,36–39] For example, Dufour et al[29] found that while RTLS technology was not accurate enough to map out specific handwashing procedures, handwashing compliance could be measured by the time spent inside and outside of a patient's room. Evaluation of RTLS integration with existing systems and perceived efficacy and usability was done via survey or semi-

Table 2. Summary of the observational RTLS articles (n = 24)

		n	%
Study type	Cross-sectional	15	62.50
	Cohort	6	25.00
	Case-controlled	3	12.50
Clinical setting	Emergency department	5	20.83
	Entire hospital	5	20.83
	Surgical ward	3	12.50
	Other	8	33.33

RTLS: real-time locating systems.

structured interviews of clinicians. Methods for evaluating the efficacy of location data capture included comparison to human observer data or the existing barcode system.

RFID or RTLS implementation

This theme addresses the facilitators and challenges of implementation, including challenges faced and problems noted postimplementation, as well as problem areas that were addressed. Two articles addressed facilitators, which described how the system is relatively easy to integrate into existing hospital standards.[40,41] Three articles addressed challenges of implementation.[16,42,43] Major challenges to successful implementation of RFID or RTLS systems included privacy concerns from both clinicians and patients, incomplete or unreliable RTLS data transmission, interference from the surrounding environment, balancing accuracy and cost, the high volume of irrelevant data extracted, and unreliable accuracy of location data. Proposed solutions to these challenges included increasing the number of sensors to improve location accuracy and setting data filtering rules to only collect data above a certain threshold to minimize irrelevant data. However, the systems can also be difficult to implement in certain high-traffic environments, such as the emergency department, and have other cost and variability limitations depending on specifics of the hospital building construction.

The mechanisms used to evaluate the effects of RTLS implementation varied widely among studies. Some used qualitative methods (eg, survey, interviews, workflow descriptions) to evaluate usability, staff acceptance, and impact.[6,32,34,44–46] Interrupted time series analyses were employed to assess waiting times after RTLS implementation.[47] Many studies utilized retrospective chart reviews and operational scheduling analyses to evaluate the impact of RTLS on clinic throughput and scheduling efficiency.[20,42,48,49] Still others conducted simulated modelling or cost utility analyses to evaluate RTLS effects on complex workflow environments.[38,50,51] Specific needs and variable clinical environments resulted in multiple applicable methods evaluating the effects of RTLS implementation.

Information visibility or accuracy

This theme addresses how well RFID or RTLS usage has improved location data visibility for to patients and care providers, as well as the accuracy and accessibility of this information. Twelve articles fall under this theme, with 6 articles citing favorable aspects and 6 articles focusing on unfavorable aspects. The favorable aspects of this theme were that RFID or RTLS technology was deemed accurate and excellent at presenting large amounts of data to clinicians.[20,45,48,52–54] However, other articles also noted that despite the high rate of data capture, the system often also indiscriminately recorded both active and resting periods of time, as well as preferentially recorded certain patterns of movement.[18,55–59]

Staff-centered workflow evaluation

This theme addresses how well RFID or RTLS has addressed workflow issues and improved communication between care providers as well as reduce overall inefficiencies within the hospital environment. Of the 8 articles that focused on this theme, none of them listed unfavorable points.[17,44,46,49–51,60,61] The major benefits that the system had for workflow improvement were in improving well-being and productivity of care providers by reducing workload, especially in chaotic environments such as the emergency department and other high-trauma-level care facilities.[44] Moreover, RFID or RTLS has provided an effective way of tracking workflow deficiencies and areas for better time management. Finally, another favorable aspect was that RFID or RTLS has promoted open dialogue between care providers and management in order to make its implementation successful and fiscally responsible.

Patient-centered workflow evaluation

This theme addresses how RFID or RTLS impacts the patient experience, including patient privacy and patient satisfaction with overall care. Only 3 articles overall addressed patient experience, and key points from the articles were that RFID or RTLS implementation can shorten patient wait times and overall inefficient time spent in clinic and can enhance patient safety.[47,62,63]

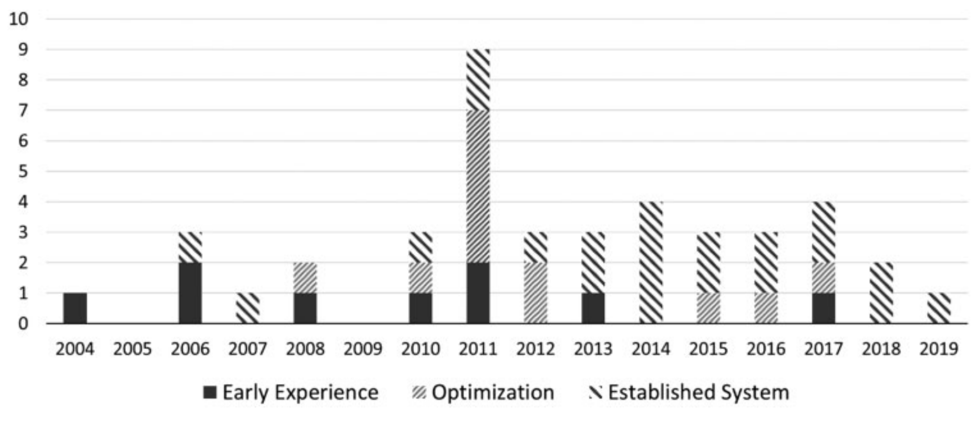

Figure 2. Categories of real-time locating systems over time.

Table 3. Themes of lessons learned

Theme	Favorable	Tags	Unfavorable	Tags
Technology evaluation	9	1. Efficient data capture 2. Convenient usage features 3. Limited interference with other medical equipment	5	1. Occasional technology failures 2. Better performance in simulation
RFID/RTLS implementation	2	1. Easy integration into hospital environments	3	1. Difficult to implement in high traffic environment 2. Cost limitations 3. Limited variability with regard to hospital building
Information visibility/accuracy	6	1. Accurate data representation 2. Multipurpose data usage	6	1. Indiscriminate data recording 2. Preferential pattern detection
Staff-centered workflow evaluation	8	1. Reduce care provider workload 2. Track workflow deficiency 3. Promote care provider team communication	0	N/A
Patient-centered workflow evaluation	3	1. Shorten patient wait time 2. Limit inefficient patient time in clinic 3. Enhance patient safety	0	N/A

N/A: not applicable; RFID: radio-frequency identification; RTLS: real-time locating systems.

RTLS in workflow research

RTLS can accurately and dependably locate patients and objects in real-world healthcare environments. Inferring clinical activities from RTLS-collected location data remains difficult. Chang et al[28] developed and validated a model to infer a contact history between caregivers and patients in an intensive care unit (ICU). Their model was able to infer "close-in," "contact," and "invasive" proximity events. When validated with direct observation, the model was shown to have good sensitivity and specificity (above 0.738 and 0.788, respectively), allowing accurate RTLS-generated contact history for tracing causes of nosocomial infections.

Other investigators evaluated clinic workflow and wait times before and after RTLS installation. Kim et al[47] conducted a time series analysis to examine changes in workflow efficiency in a health promotion outpatient clinic. The system displayed real-time workflow information such as duration of handwashing and times of examinations and combined them with an existing health information system. When comparing a control group with the pre- and post-RTLS group, they found that the mean waiting time of patients decreased after the implementation of RTLS.

As RTLS adoption and installation became more widespread, investigators applied its capabilities to address specific workflow challenges. Five studies focused on clinician locations and interactions.[18,20,30,38,62] Seven studies evaluated interventions that may improve RTLS-measured patient wait times.[34,36,43,49,51,60,61] Three articles evaluated differences in RTLS-measured outcome measures compared with traditional methods of measuring workflow.[39,42,48]

In addition, investigators have worked to create enhanced descriptions of operational efficiency. Multiple studies utilized RTLS to describe proportions of time in which clinicians are colocated with patients (ie, "face-time efficiency"). Arunachalam et al[55,60] studied the relationship between patient alone time and overall length of stay in the emergency department. While they did not find a correlation between alone time and higher length of stay, they reported the utility of using RTLS to dissect a patient visit into various operational components amenable to rigorous analysis. Another study analyzed "face-time efficiency" in an outpatient clinic and found an improvement in workflow when interruptions in face time were minimized.[20] RTLS was found to more accurately reflect the time during which patients were not face to face with clinicians and were occupying exam rooms. Another study noted that shorter face time was associated with shorter overall length of stay but with more radiology test ordering in a primary care setting.[43] These findings were not replicated in urgent care settings, suggesting that RTLS may enhance our understanding of the trade-offs between face time, test ordering, and length of stay in various healthcare environments.

Stahl et al[36] used RTLS as a method to unobtrusively observe the effects of a natural experiment involving a preplanned process change in an outpatient clinic, designed to optimize the use of medical assistants and the waiting room. They found a change in the use of time patients spent in the waiting room vs the exam room after the intervention. RTLS was demonstrated to be an excellent method to measure behavioral changes and process improvements in cramped physical environments with dynamic patient and staff interactions.

Challenges and limitations in RTLS research

This systematic review summarizes the lessons learned and generated 5 themes, which are consistent with the RTLS implementation experience in our institution. Startup and maintenance costs of the RTLS system often limited the size and scale of RTLS workflow testing.[16,18,56] Artificial simplification of complex tasks for testing purposes, or overly simplified simulation, may significantly limit the generalizability of these studies.[45,47,56] Additionally, movement data were often cited as a proxy measure for as assumed activity, for which it may not be completely accurate.[35,56] Implementation of RTLS required consideration of the physical environment and workflow. Small spaces and frequent brief movements required strategic planning to integrate virtual RTLS maps with physical environments, and to balance the accuracy needs of the investigators with installation costs.[16,37,45,59] Other challenges included initial staff hesitation to adopt the technology and personal badges, citing privacy concerns and disinterest. This challenge was overcome with publicity campaigns to encourage staff buy-in and enhancing privacy with cryptography, signal processing, and hardware design.[19,35,47]

An interesting challenge which is rarely highlighted, but frequently present, is the need to triangulate the movement data against an additional, separate data stream, usually to provide context to existing data, or to validate completeness of questionable or duplicate data.[20,47,57] Many authors encountered issues with data completeness due to issues with hardware or software transmissions, badge wearing compliance, and environmental interference.[16,18,20,56,57] Limited geographic coverage for testing within a larger hospital setting or limited hardware coverage may lead to incomplete or ambiguous data.[18,42,45,52,57] Solutions to these problems included installation of antennae on equipment to boost signal transmission, software-based signal attenuation, and redesign of RTLS hardware to complement the physical environment.[42,56]

The incredible volume of data encountered in these studies is often cited as a significant challenge. In an effort to limit the volume, several authors created up-front filtering rules, which limited the quantity of data captured, but Miller et al[18] found that too much data were lost using this technique, and ultimately captured all data for completeness.[16,36] Stahl et al[36] found that the data stream required significance postprocessing to convert raw location data into a usable form for time-motion studies. Once generated, filtering out background noise was often described as time-consuming and labor-intensive.[56,57] During early studies, simple algorithms were created to sort out relevant time data from background noise, or to correct probable anomalous data findings.[36,49,56] Later strategies included data cleaning to scrub duplications and remove discrepant data from badges that were left motionless for long periods of time.[57]

To address these challenges, researchers have worked to create solutions to incorporate the benefits of RTLS-derived data with advanced analytic modelling techniques. As Vankipuram et al[38] describe, typical methods of workflow analysis (ie, observation, ethnography) are suboptimal due to the complexity of clinical environments. They have worked to develop quantitative means to capture and analyze workflow using hidden Markov modelling to handle the variations in clinical locations and flow. They used RTLS-produced data to train a hidden Markov model and create activity recognition to visualize and analyze clinical events in an emergency department trauma bay.

This work was continued in the creation of an analytic framework to develop RTLS exploratory capacity to augment traditional qualitative techniques in an ED. Their framework combines estimations of entropy, actor interactions, location probabilities, and common subsequences to analyze RTLS data.[62] The authors concluded that this framework may allow for effective analysis of patterns and behaviors in real-time, and assessment of the impact of process changes. Additionally, it may enhance RTLS error analysis where the data noise reduction and localization capabilities of the RTLS software may not be adequate.

DISCUSSION

Main findings

This systematic review summarized the existing literature on the use of RTLS to enhance healthcare delivery. We identified 42 articles on the use of RTLS to improve healthcare delivery. We found no articles published prior to 2004. From 2004 to 2019, we describe a temporal shift moving from early experience (RTLS installation and technical feasibility) to optimization and maturing established systems. Among the themes of lessons learned, there was equipoise in successes and challenges in the themes of technology evaluation, RTLS implementation and information visibility or accuracy. Published studies found more success in workflow evaluation among staff and patients. Many observational studies focused on clinician location and interactions and comparing RTLS-measured event characteristics with traditional methods (ie, staff recall). While there are few studies using RTLS to assess patient wait times, more research is needed to utilize this valuable resource to improve patient experience. More recently, some studies have worked to develop advanced methods of analysis to derive meaningful conclusions from RTLS data while accounting for voluminous data and the inherent chaos captured by the system.[38,62]

Novelty of this review

To our knowledge, this is the first systematic review to investigate the use of RTLS to improve healthcare delivery that includes both patient and staff tracking and specifically reviews the quantitative analysis measures and summarizes lessons learned. Previous reviews focused on the technical specifications of RTLS installation, applications, potential benefits, and barriers to success.[64,65] For example, Coustasse et al[66] examined RFID systems in transfusion medicine and noted overall potential benefits realized by tracking blood product from time of donation to transfusion. Other reviews focused patient tracking and noted the generally favorable experiences with RTLS in the literature. Dobson et al[67] performed a systematic review focusing on patient tracking systems in pediatric emergency departments. They concluded that, while RTLS can be used to document patient flow, improve patient safety, and enhance emergency department throughout, there was a paucity of methodologically sound quantitative studies. More recently, Ebrahimzadeh et al[68] performed a systematic review evaluation RTLS technology in patient tracking in hospitals. Both these reviews focused on patient tracking and noted the generally favorable experiences with RTLS in the literature. However, these reviews did not include studies that investigated the use of RTLS in other healthcare workflow applications.

Implementation in health care

The healthcare industry has been relatively slow to adopt and integrate RTLS compared with commercial and government entities. RTLS-related work in health care has increased since 2010. Our findings show an increase in the proportion of literature that describes case-control study design in established systems in recent years, reflecting some maturation of RTLS in health care. Conversely, early studies focused on experiential descriptions of installation, compatibility, and technical feasibility in healthcare environments.

Descriptive studies had 2 primary focuses: the feasibility of the system implementation and staff acceptance of the system. Most studies combined a description of the feasibility of system implementation with staff surveys measuring their perception of the system.[6,33,45,54,57] Survey perceptions were generally favorable around operability and accuracy of the system. Similar to other commercial applications, privacy was cited during surveys as a persistent concern.[33,47] Multiple authors allude to early human factors, such as encouraging staff buy-in, but do not address the training or interventions used.[32,54]

Limitations

Our study has several limitations. First, we only searched articles in English and ignored articles written in other languages. Second, while we searched multiple databases using an inclusive search strategy, it is possible that some articles were overlooked due to the design of the search keywords. However, we believe the search keywords are comprehensive enough to cover most of the articles of interest based on our iterative testing. Third, we were unable to review relevant but unpublished manuscripts, presentations, and data.

Future directions

While some studies have focused on improving health outcomes such as patient or medication identification,[45] airway risk classification,[34] and handwashing,[29] most focus on operational improvements, efficiency, and wait times. Further work is needed to demonstrate direct improvements in health outcomes from RTLS applications. Future directions should focus on continuing to develop enhanced analysis methods to extract meaningful patterns from these massive RTLS data. Clearly specifying the role of RTLS at the outset of project development may help researchers focus on the metrics and processes most amenable to RTLS application. Further work should attempt to reduce noise and glean actionable conclusions from location data while minimizing manual data management and interpretation. We did not find any studies specifically examining how data infrastructure and procedures most effectively analyze RTLS-produced data. Thus, optimization of analysis procedures (ie, data transformation, filtering, and reporting) is a potential area for improving the efficiently with which RTLS can address relevant clinical workflow questions. Additionally, more research utilizing RTLS data to measure and improve staff satisfaction and patient experience may expand the role of this promising technology in health care.

CONCLUSION

This review has shown RTLS to be a useful and effective adjunct to traditional methodologies used in process and quality improvement, workflow analysis, and patient safety. While challenges in implementation, data management, and analysis remain, our outlook on the future of RTLS in health care is optimistic. Further work is warranted to expand the scope of clinical processes to which RTLS is applied and to develop robust analytic frameworks to improve our understanding RTLS data in healthcare environments.

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AUTHOR CONTRIBUTIONS

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by KMO, CTX, SSB, and DTYW. The first draft of the manuscript was written by KMO and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

SUPPLEMENTARY MATERIAL

Supplementary material is available at *Journal of the American Medical Informatics Association* online.

DATA AVAILABILITY STATEMENT

The data underlying this article will be shared on reasonable request to the corresponding author.

CONFLICTS OF INTEREST STATEMENT

The authors have no conflicts of interest to disclose.

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