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Contact Tracing using Real-Time Location System (RTLS): A Simulation Exercise in a Tertiary Hospital in Singapore

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ABSTRACT

Background

Metropolitan cities like Singapore are susceptible to emerging infectious disease (EID) outbreaks. Singapore's pandemic control measures include running biennial simulation exercises for all public hospitals on EID case management, where a key assessment criterion is contact tracing.

Local Problem

Current contact tracing methods are time consuming, heavily manpower dependent, and fail to capture a significant number of contacts. Real-time location system (RLTS) was found to be accurate and effective in contact tracing. This study investigates the effectiveness of RTLS, and whether RTLS provides any time, manpower and cost savings.

Methods

A prospective case study was conducted during a simulation exercise to determine and compare the list of contacts, time taken, manpower, and manpower-hours required between RTLS and conventional methods of contact tracing. Cost of both methods were compared.

Results

RTLS identified almost three times the number of contacts compared to conventional methods, while achieving that with significantly less time, manpower, manpower-hours, and manpower cost. However, RTLS incurred significant equipment cost and might take many contact tracing episodes before providing economic benefit.

Conclusion

Albeit costly, RTLS is effective in contact tracing. RLTS might not be ready at present time to replace conventional methods, but with further refinement, RTLS has the potential to be the gold standard in contact tracing methods of the future, particularly in the current pandemic.

ARTICLE SUMMARY

Strengths and limitations of this study

Strengths

1. Quantified contacts identified, and time elapsed/taken by RTLS and EMR

2. Quantified manpower, manpower hours, manpower cost, equipment cost by both methods

Limitations

1. Lack of gold standard in identifying true contacts

2. Study based on one simulation exercise in one institution

3. Impact & cost savings of halting disease transmission earlier not studied

INTRODUCTION

Metropolitan cities like Singapore, which are densely populated and receive a high volume of international visitors, are highly susceptible to emerging infectious disease (EID) outbreaks. Some examples in the last decade include Ebola virus disease (EVD) outbreaks within and out of West Africa in 2014 and Middle East respiratory syndrome coronavirus (MERS-CoV) outbreak in South Korea in 2015[1]. Singapore had its own experiences with the Nipah virus outbreak in 1999, the severe acute respiratory syndrome (SARS) outbreak in 2003, and the influenza A (H1N1) outbreak in 2009[2], and most recently, COVID-19. As such, Singapore needs to continually strengthen its defences against EID outbreaks[1]. Founded on the experiences of previous outbreaks, Singapore took a "whole-of-government approach" towards implementing pandemic control measures[2]. In order to test these measures, the Ministry of Health (MOH) requires all public hospitals to participate every two years in a national simulation exercise[1,3], and be validated in the management of an infectious disease case. A key assessment criterion of the exercise is contact tracing.

Contact tracing, a systematic process of identification, assessment, and management of people exposed to the disease, is a critical element in containing any outbreak[4]. Current methods of contact tracing involve retrospective review of multiple databases, such as electronic medical records (EMR) entered by healthcare workers, hospital registration systems capturing patient journeys in the hospital, and visitor management systems capturing registered visitors to the hospital. After a preliminary list of potential exposures, also known as contacts, is compiled, individual interviews are carried out to identify any other contacts that were not included by the above systems. These conventional methods are time consuming, heavily manpower dependent, and fail to capture a significant number of contacts[5]. This is because the databases used were not primarily designed to identify contacts between individuals[6] and do not provide enough detail to accurately derive a list of contacts. Failure to trace contacts in a timely and accurate manner can lead to continued transmission of diseases, preventing effective control of EID outbreaks.

Radio frequency identification (RFID) technology, which involves fixed readers receiving signals from small ID tags[7], is widely used in many industries such as commerce and logistics. Tagged items can be identified, tracked and managed in real-time through a centralised database and a compatible device[7]. RFID tags are broadly categorised into active or passive tags[7,8]. Active tags have power sources of their own, allowing them to transmit signals as well as the potential for additional functions. Passive tags have no power sources and depend on RFID readers for power, hence having relatively fewer functions. However, active tags are bigger, costlier, and require regular charging and maintenance compared to passive tags. RFID technology is increasingly being adopted for many uses in healthcare settings such as asset and equipment tracking, staff and patient identification, sensing, intervention, and alerts and triggers[8]. These applications provide improvement in patient safety, reduction in medical errors, time and cost savings and improved medical processes[8]. Another potential application of the RFID technology is a real-time location system (RTLS) allowing tracking of interactions among individuals[5]. RTLS using RFID technology was used to study the relationship between the contact patterns of individuals and the spread of infectious diseases via a simulation exercise in an academic conference of 1200 attendees[9]. The use of RTLS in the inference of contact history between healthcare staff and patients has also been studied in two settings. In an intensive care unit of a hospital in Taiwan, contact tracing using RTLS was found to be effective with 81.4% sensitivity, 78.8% specificity and 80.7% accuracy[6]. In an emergency department of a tertiary care medical centre in the United States, RTLS doubled the number of contacts identified compared with the conventional method of EMR review[5].

To date, few studies have evaluated the clinical and economic impact of contact tracing using RTLS compared to conventional methods. RTLS has been found to be an accurate and effective way to perform contact tracing, however, little is known as to whether the accuracy and efficacy translates to earlier cessation of forward transmission, as well as whether RTLS provides any manpower and monetary cost savings.

In this study, we aim to assess the effectiveness of contact tracing using RTLS compared to the conventional (EMR) method via an EID outbreak simulation exercise in Sengkang General Hospital, Singapore. The aims of the study are:

1. To compare the time taken to perform contact tracing and list of contacts identified for RTLS vs EMR.
2. To compare manpower and manpower-hours required to perform contact tracing for RTLS vs EMR.

The cost incurred by both methods were studied.

We hypothesised that contact tracing using RTLS would allow us to identify contacts in a timelier and more accurate fashion, facilitating earlier cessation of forward transmission and better control of an EID outbreak. We also hypothesized that contact tracing using RTLS would confer benefits in manpower and manpower-hours reduction, which would translate to cost savings for the hospital.

MATERIALS AND METHODS

Context

This study was held in Sengkang General Hospital (SKH), a 1000-bedded public acute hospital in Singapore with a staff of 4000. This study was conducted in Feb 2019, at a point when SKH was receiving 3149 admissions and 8172 emergency department visits per month. The study was conducted during a national simulation exercise on EID outbreaks held every two years. In this exercise, a surgical patient with a three-day inpatient stay was selected as the simulated MERS-CoV index case. This patient was admitted through the emergency department, underwent surgery in the operating theatre on Day 1 and spent three days in an inpatient ward.

Equipment

The RTLS used for contact tracing in our hospital was based on SmartSense Solutions infrastructure and SmartSense RTLS platform provided by Cadi Scientific. Staff tags and patient tags, which were both active RFID tags, were deployed. The staff tags were additionally equipped with an antenna that captured tag interactions within a two-metre radius of itself. Tag signals were picked up by the campus-wide network of in-ceiling wireless receivers and exciters. Our RTLS was tested and operational prior to the data collection. As a pilot study, 1000 out of 4000 staff wore staff tags. The selected 1000 staff included doctors and nurses working in high risks areas such as the Emergency Department and the inpatient wards. The rest of the staff, including the remaining doctors, nurses, allied health professionals, ancillary staff, and students were not equipped with staff tags. All patients wore patient tags from registration to discharge. Our RTLS platform captured two forms of contact: (1) tag-to-tag based, and (2) location based. A tag-to-tag based contact was registered when any tags (staff or patient) were detected within a two-metre radius of a staff tag for at least a one-minute duration. A location based contact was registered when any tags were detected within the same location for at least a one-minute duration. Location of tags were determined via WiFi triangulation and chokepoint tracking[7,11].

Measures

A prospective case study was conducted during the biennial national simulation exercise in Sengkang General Hospital on 28 Feb 2019 to determine the list of contacts, time taken, manpower required, and manpower-hours required to perform contact tracing via both RTLS and the conventional method of databases review (EMR). The date of the exercise was unannounced, with the contact tracing team activated only at the point of the exercise itself. All staff involved in contact tracing were briefed prior to the exercise to record the amount of time spent on performing the work of contact tracing.

Intervention

During the simulation exercise, two concurrent contact tracing team performed contact tracing, one via conventional method (EMR), and the other via RTLS. The hospital contact tracing team, which comprised nurse leadership in coordination with hospital infection control, performed contact tracing via conventional methods as per existing hospital contact tracing protocol. Firstly, an activity map of the index case, comprising the journey within the hospital, was derived after reviewing the EMR. Subsequently, a list of contacts comprising healthcare workers, other patients, and hospital visitors, was compiled via various databases. The EMR identified any healthcare workers who documented their interactions with the patient, the hospital registration system identified other patients who were in the same location as the index case, and the visitor management system identified visitors who registered to visit the location of the index case.

Concurrently, the other team generated the activity map and the list of contacts using the RTLS platform. The activity map showed the entire journey within the hospital, depicting each

location and the duration the index case visited. The list of contacts was then derived for each of these locations, depicting the time and duration of each staff and patient the index case came in contact with.

Analysis

Between the two methods used for contact tracing, we compared the time taken, manpower required, manpower-hours required, and the list of contacts identified. Between the two contact lists, we compared the number of contacts, and the roles of these contacts (doctors, nurses, allied health workers, ancillary staff, patients, or visitors). As a significant proportion of the existing staff were not equipped with the staff tags at that point of the study, the comparison between the lists was done primarily on staff equipped with the tags. Descriptive statistics were used to compare the two methods.

Patient and Public Involvement

It was not appropriate or possible to involve patients or the public in the design, or conduct, or reporting, or dissemination plans of our research.

Ethical Considerations

This study was reviewed and approved by the SingHealth Centralised Institutional Review Board.

RESULTS

Simulation Exercise

The index case had a length of stay of three days and seven minutes and visited three main locations in the hospital: emergency department, operating theatre, and inpatient ward. RTLS alone identified 226 unique contacts, of which there were 157 staff and 69 patients. EMR alone identified 288 unique contacts, of which 82 (27 staff and 55 patients) were tagged (Table 1). For a better comparison of results, subsequent comparisons were made using only tagged staff and patients, focusing only on the tagged staff EMR identified.

Out of a total of 260 unique contacts, RTLS identified 226 while EMR (tagged) identified 82, with an overlap of 48 (Table 2 & Figure 1). RTLS yielded an additional 178 contacts over the 82 contacts EMR (tagged) yielded, giving an additional 217.1% unique contacts. Out of all the unique contacts, RTLS detected 86.9% while EMR detected 31.5%.

The comparison is further broken down into the three locations visited by the index case, namely the emergency department (ED), the operating theatre (OT) and the inpatient ward. RTLS yielded the highest increase of 263.3% in unique contacts in the ward, and lowest increase of 66.7% in the OT (Table 2 & Figure 1). Interestingly, RTLS yielded an increase of 870.0% unique staff contacts over EMR in the ED.

On comparison of the time taken, manpower required, and manpower-hours required, RTLS took 0.9h, 1 manpower, and 0.9 manpower-hours while EMR took 23.7h, 42 manpower, and 35.3 manpower-hours (Table 3). RTLS provided a 96.2% reduction in time taken, 97.6% reduction in manpower, and 97.5% reduction in manpower-hours required. By RTLS, only one staff was required to acquire the activity map and contact list. Conversely, by EMR, two staff from the infection control department were needed to lead the contact tracing efforts, involving 24 additional departments and 40 other staff in the process.

In terms of hospital costs, RTLS required an equipment cost (RTLS platform and staff tags) of $653,594 for the first three years to purchase and maintain the system, whereas EMR method required no additional equipment cost. In terms of manpower costs computed over the simulation exercise, RTLS method incurred a manpower cost of $62 per contact tracing episode, whereas EMR method incurred a manpower cost of $2,125. We computed the expected expenditure over three years to evaluate the long-term cost between RTLS and EMR, as the staff tags had an estimated lifespan of three years. We found that at least 317 contact tracing episodes were needed in the three-year period to obtain cost benefit for RTLS (Table 4).

DISCUSSION

Summary

Overall, RTLS identified almost three times the number of contacts compared to EMR, while achieving that with significantly less time, manpower, manpower-hours, and manpower cost. One caveat to RTLS that may be prohibitive to its implementation is its high cost of entry as the equipment cost incurred can be significant and might take many contact tracing episodes to occur before providing economic benefit.

Interpretation

Similar to the study in Mayo Clinic that found RTLS to have identified 100% more contacts than EMR[5], our study found RTLS to have identified 217.1% more contacts (Table 2). Interestingly, RTLS identified a large increase of 870.0% unique staff contacts in the ED (Table 2). We found that the reason behind that was unique to the ED, where off-duty staff kept their tags in lockers situated within the ED. This resulted in some RTLS staff contacts in the ED to be falsely positive when the index case came in proximity to those lockers. The other RTLS contacts within the ED, the OT, and the ward were found to otherwise be largely accurate. They were identified by RTLS but not EMR for reasons such as doctors and nurses reviewing patients other than the index case, but physically within proximity to the index case. RTLS also detected nurses who chaperoned patients other than the index case to the OT and came in proximity to the index case. Other instances found patients who were physically within the ED as detected by RTLS but omitted by EMR as they were logged as already "discharged" within the EMR system. The value proposition of the RTLS is its capability in detecting such contacts which would otherwise be difficult to establish in the current systems.

While RTLS identified more contacts than EMR, the overlap was not as expected. Out of the 82 EMR contacts, only 48 were identified by RLTS, with 34 (6 staff and 28 patients) unidentified by RTLS (Figure 1). Subsequent analysis of this discrepancy at the three locations (Figure 1) revealed that a large number were detected by RTLS as being in different sub-locations from the index case, whether it was in the ED, the OT or the ward. In some cases, RTLS even detected them in completely different locations, which was a result of some lag time in the manual update of the EMR system when patients were transferred between locations. This suggests a lack of fidelity in the EMR system for contact tracing, resulting in falsely positive EMR contacts. In a few cases, staff tags were found to be improperly charged or worn, resulting in the tags being completely undetected or detected in irrelevant locations.

Although not specifically comparable to EMR, the study in the Taiwan hospital found RTLS to have good sensitivity, specificity and accuracy[6]. In our study, RTLS proved to be effective in the identification of contacts as it possibly has better sensitivity than EMR as shown by the identification of contacts that went undetected by EMR, and better specificity by showing some contacts detected by EMR to be false positives due to the subdivision of locations in the RTLS platform. However, non-compliance to charging and wearing of tags proved to limit the effectiveness of RTLS in the detection of contacts. To circumvent such limitations, more staff education and training can be implemented to emphasize the appropriate usage of staff tags. Future tags designs could also be integrated into existing staff cards, which are required for staff to gain access into hospital compound and staff-restricted areas within the campus, thus resolving some of the compliance issues faced in this study.

Aligned with the study in Mayo Clinic that estimated RTLS to take <5 minutes while EMR to take 30-60 minutes[5], our study found RTLS provided significant time, manpower, and manpower-hour savings of 96.2%, 97.6% and 97.5% respectively (Table 3). Although not specifically measured and compared with other contact tracing episodes, it is expected that RTLS can consistently deliver similar results regardless of the index case's length of stay, number of locations visited, number of departments involved (e.g. allied health professionals' involvement), or day of contact tracing (weekday vs weekend). With EMR, anecdotal evidence revealed that longer lengths of stay, larger numbers of locations visited, larger numbers of departments involved, as well as contact tracing over a weekend can all result in significant delays in contact tracings. Moreover, should all staff in the hospital be tagged, the objective data provided by RTLS would reduce the subsequent work of verification and interview with each contact. Perhaps, the RTLS platform can also be designed to coordinate with other hospital communication systems to trigger automated text messages or emails to be sent to the affected individuals, further reducing the downstream workload of the contact tracing team.

Our cost computations found that initial investment on the RTLS equipment can prove to be costly and present a significant barrier to entry, requiring about two contact tracing episodes per week for RTLS to warrant the investment, while an average of two contact tracing episodes occurred monthly in our hospital (pre-COVID). It is found in other studies that RTLS can be justified in large urban healthcare institutions with diverse patient populations, but not so in small community healthcare institutions[5]. Further studies are required to evaluate and justify the cost of RTLS in Singapore. Alternatively, future studies can look into the cost-benefit analysis of tagging certain groups of the healthcare staff over the others, hence lowering the equipment cost of RTLS.

Limitations

Our study had some important limitations. The results of our study are based on one simulation exercise in our institution, hence limiting generalisability. Factors such as index case length of stay, number of locations visited, number of departments involved, or the day contact tracing was performed could all influence the results and necessitate further investigations. Despite the absence of any prior notice, the simulation exercise was held within a month of two prior rehearsals. As such, heightened sense of awareness among hospital staff that an exercise was about to occur, coupled with a possible Hawthorne effect of a simulation exercise, could have resulted in shorter than usual response time. As contacts of the index case were not observed prior to contact tracing, there were no definitive means of determining the true positives and negatives of both methods, though the RTLS was tested and deemed operational prior to the data collection. Also, only 1000 permanent staff deemed working in high-risk areas were tagged. However, our EMR contacts revealed significant untagged populations such as junior doctors on six-month rotations, allied health professions, and ancillary staff providing meals, cleaning, and porter services. These groups of people were under-represented in this study and their inclusion may result in different contact activities.

Early recognition and mitigation of an EID is paramount in impeding the multiplicative effect of any outbreak, potentially limiting its transmission towards a widespread epidemic. Other studies showed contact tracing to be critical in halting disease transmission[13], and further studies possibly with computational models can more accurately show the clinical benefits conferred by performing contact tracing with RTLS.

Current cost computations consist of only equipment and manpower costs, without considerations on the economic impact of reducing disease transmission. Future studies taking into account the economic impact of reducing disease transmission, particularly in COVID-19, might show RTLS to confer greater economic benefits than presented in this study.

Conclusion

Compared to EMR, we found that RTLS identified contacts in a timelier and more accurate fashion, required fewer manpower and manpower-hours, and has the potential to limit disease transmission. Despite the advantages, high equipment cost is incurred with RTLS and might present significant barrier to adoption. RLTS might be at a nascent stage and not be ready to completely replace conventional methods in contact tracing. However, with subsequent cycles of plan-do-study-act (PDSA)[14] and further studies taking into account the economic impact of reducing disease transmission, RTLS has the potential to be the gold standard in contact tracing methods of the future.

This study explicitly examines the time, manpower, manpower-hours, reduction in disease transmission, and cost of performing contact tracing between RTLS and other conventional means. Our findings hold implications for hospital administrators and healthcare regulators, especially within the country, to relook at how existing standards of contact tracing can be improved.

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- ☐ Substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data for the work; AND
- ☐ Drafting the work or revising it critically for important intellectual content; AND
- ☐ Final approval of the version to be published; AND
- ☐ Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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- ☐ Drafting the work or revising it critically for important intellectual content; AND
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TABLES

Table 1 Comparison of contact list breakdown identified by real-time location system (RTLS) and electronic medical record (EMR). Table created by authors.

Role	RTLS	EMR		
		Tagged	Untagged	Total
Healthcare Workers	157	27	110	137
- Doctors	*8*	*2*	*39*	*41*
- Nurses	*149*	*25*	*19*	*44*
- Allied Health Professionals	*0*	*0*	*11*	*11*
- Ancillary Staff	*0*	*0*	*41*	*41*
Patients	69	55	0	55
Visitors	0	0	96	96
Total	226	82	206	288

Table 2 Comparison of contact list between RTLS and EMR (Tagged) by role only, and by location/role. Table created by authors.

Role	RTLS	EMR (Tagged)	RTLS (but not EMR)	Both RTLS & EMR	EMR (but not RTLS)	Total unique contacts	RTLS increase over EMR (%)
Healthcare Workers	157	27	136	21	6	163	503.7
- Doctors	*8*	*2*	*7*	*1*	*1*	*9*	*350.0*
- Nurses	*149*	*25*	*129*	*20*	*5*	*154*	*516.0*
Patients	69	55	42	27	28	97	76.4
Total	226	82	178	48	34	260	217.1
[a] Detection rate (%)	86.9	31.5				100	175.6
Location / Role	**RTLS**	**EMR (Tagged)**	**RTLS (but not EMR)**	**Both RTLS & EMR**	**EMR (but not RTLS)**	**Total unique contacts**	**RTLS increase over EMR (%)**
Emergency Department	114	47	90	24	23	137	191.5
- Staff (doctors & nurses)	*94*	*10*	*87*	*7*	*3*	*97*	*870.0*
- Patients	*20*	*37*	*3*	*17*	*20*	*40*	*8.1*
Operating Theatre	12	9	6	6	3	15	66.7
- Staff (doctors & nurses)	*5*	*1*	*4*	*1*	*0*	*5*	*400.0*
- Patients	*7*	*8*	*2*	*5*	*3*	*10*	*25.0*
Ward (Inpatient)	101	30	79	22	8	109	263.3
- Staff (doctors & nurses)	*54*	*16*	*41*	*13*	*3*	*57*	*256.3*
- Patients	*47*	*14*	*38*	*9*	*5*	*52*	*271.4*

*[a] Detection rate = [(Contacts detected by either methods)/(Total unique contacts)]*100%*

Table 3 Comparison of time taken, manpower required, and manpower-hours required between RTLS and EMR. Table created by authors.

RTLS

Process	[a] Elapsed time (h)	[b] Manpower required	Manpower-hours required (h)
Index case identified	0	0	0.0
Activity map: Generate activity map via SmartSense	0.1	1	0.1
Activity map: Sort data and fill of MOH activity map template	0.5	1	0.4
Contact list: Generate contact list via SmartSense	0.6	1	0.1
Contact list: Review and sort contact tracing data, and fill MOH contact list template	0.9	1	0.3
	[a] 0.9	[b] 1	0.9

Downstream Departments	Manpower required	Manpower-hours required (h)
None	0	0.0

EMR

Process	[a] Elapsed time (h)	[b] Manpower required	Manpower-hours required (h)
Index case identified	0	0	0.0
Activity map: SAP check (hospital registration system)	0.1	1	0.1
Activity map: Contact OT (OT journey)	0.5	1	0.4
Activity map: SCM check (EMR)	0.6	1	0.6
Activity map: Contact ED (ED journey)	0.8	1	0.3
Activity map: Verify data and fill of MOH activity map template	1.5	2	0.8
Contact list: Contact MI (list of exposed patients)	1.7	1	0.2
Contact list: Email all stakeholders - ED, OT, Ward, AHP (13dept), Anc staff (5dept)	1.9	1	1.1
Contact list: Contact AVMS (list of exposed visitors)	2.2	2	0.4
Contact list: Sort MI data (list of exposed patients)	3.9	1	0.2
Contact list: Contact IHIS (author list of EMR)	4	1	0.2
Contact list: Sort IHIS data (author list of EMR)	7.2	1	0.5
Contact list: Compile data, call and clarify non-response / missing data, and fill MOH contact list template	23.7	2	12.0
	[a] 23.7	[b] 2	16.4

Downstream Departments	Manpower required	Manpower-hours required (h)
Emergency Department	1	1.3
Operating Theatre	1	1.0
Ward 19	1	1.0
Management Information - eHints	1	0.5
AVMS dept	4	2.5
Integrated Health Information Systems	2	1.5
Audiology	1	0.2
Clinical Measurement Centre	1	0.1
Dietetics	1	0.1
Medical Social Services	1	0.2

				Occupational Therapy		1	0.3
				Pathology		1	0.1
				Pharmacy		2	0.7
				Physiotherapy		3	1.2
				Podiatry		2	0.5
				Psychology		1	0.3
				Radiology		1	0.5
				Respiratory Therapy		1	0.8
				Speech Therapy		1	0.2
				Environmental Services		6	1.8
				Facilities Management & Engineering		1	2.0
				General Services		2	1.2
				Materials Management		1	0.8
				Security		3	0.3
		0	0.0			40	18.9
	[a] Elapsed time (h)	**[b] Manpower required**	**Manpower-hours required (h)**		**[a] Elapsed time (h)**	**[b] Manpower required**	**Manpower-hours required (h)**
Total	**[a] 0.9**	**[b] 1**	**0.9**	**Total**	**[a] 23.7**	**[b] 42**	**35.3**
Decrease over EMR (%)	**96.2**	**97.6**	**97.5**				

[a] *Elapsed time refers to the amount of time that has passed since the start of the exercise at the point of completion of a process, hence the total elapsed time is not a simple sum of the above cells.*

[b] *Manpower required is the number of staff it took to perform the process. Many of the processes were performed by the same staff, and hence the total manpower required is not a simple sum of the above cells.*

Table 4 Comparison of cost between RTLS and EMR. Table created by authors.

Cost	**RTLS**	**EMR**
[a] Equipment cost (for first three years)	$653,594	$0
[b] Manpower cost (for each contact tracing episode)	$62	$2,125
Case scenarios		
36 contact tracing episodes in 3 years	$655,826	$76,500
156 contact tracing episodes in 3 years	$663,266	$331,500
317 contact tracing episodes in 3 years	$673,248	$673,625

[a] *Equipment cost (RTLS) = cost of RTLS platform + cost of staff tags*

[b] *Manpower cost = (manpower-hours of Staff 1 * norm cost of Staff 1) + (manpower-hours of Staff 2 * norm cost of Staff 2) + … + (manpower-hours of Staff N * norm cost of Staff N)*

FIGURES

Figure 1 Comparison of RTLS vs EMR (tagged) broken down into: (a) total - staff & patients, (b) total - staff (doctors & nurses), (c) total - patients, (d) ED - staff (doctors & nurses), (e) ED - patients, (f) OT - staff (doctors & nurses), (g) OT - patients, (h) Ward - staff (doctors & nurses), and (i) Ward - patients. Figure created by authors.

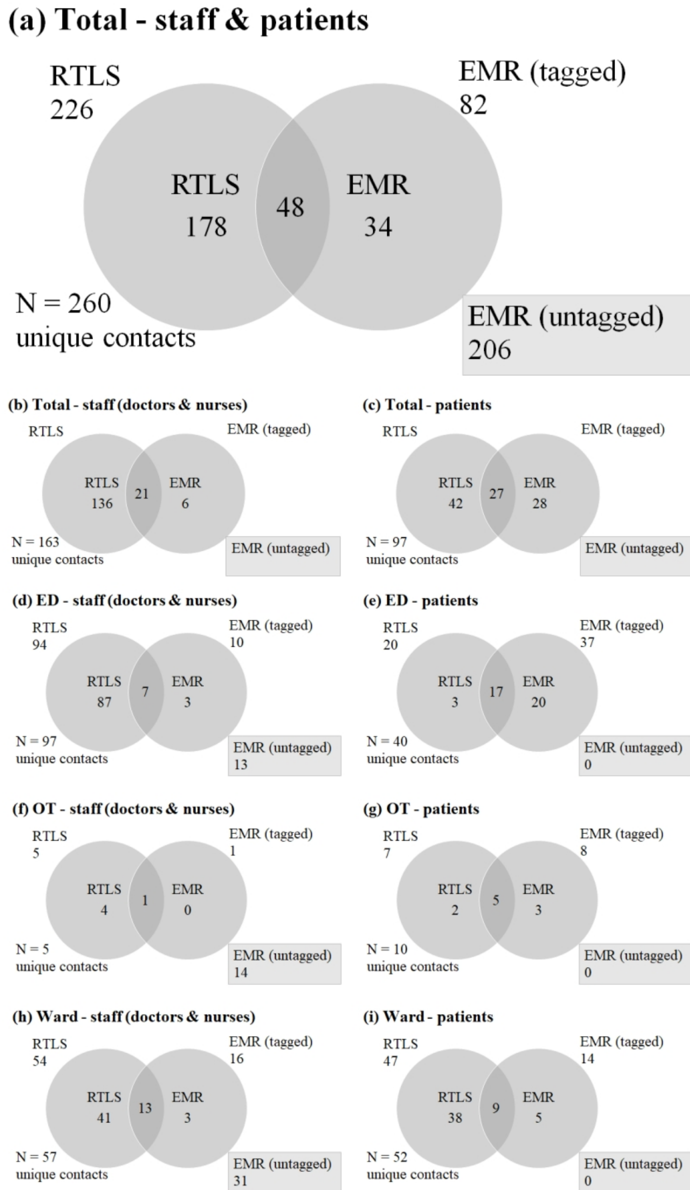

Figure 1 Comparison of RTLS vs EMR (tagged) broken down into: (a) total - staff & patients, (b) total - staff (doctors & nurses), (c) total - patients, (d) ED - staff (doctors & nurses), (e) ED - patients, (f) OT - staff (doctors & nurses), (g) OT - patients, (h) Ward - staff (doctors & nurses), and (i) Ward - patients. Figure created by authors.

618x1060mm (47 x 47 DPI)

Revised Standards for Quality Improvement Reporting Excellence (SQUIRE 2.0)
September 15, 2015

Text Section and Item Name	Section or Item Description	
Notes to authors	• The SQUIRE guidelines provide a framework for reporting new knowledge about how to improve healthcare • The SQUIRE guidelines are intended for reports that describe system level work to improve the quality, safety, and value of healthcare, and used methods to establish that observed outcomes were due to the intervention(s). • A range of approaches exists for improving healthcare. SQUIRE may be adapted for reporting any of these. • Authors should consider every SQUIRE item, but it may be inappropriate or unnecessary to include every SQUIRE element in a particular manuscript. • The SQUIRE Glossary contains definitions of many of the key words in SQUIRE. • The Explanation and Elaboration document provides specific examples of well-written SQUIRE items, and an in-depth explanation of each item. • Please cite SQUIRE when it is used to write a manuscript.	
Title and Abstract		Page
1. Title	Indicate that the manuscript concerns an initiative to improve healthcare (broadly defined to include the quality, safety, effectiveness, patient-centeredness, timeliness, cost, efficiency, and equity of healthcare)	1
2. Abstract	a. Provide adequate information to aid in searching and indexing b. Summarize all key information from various sections of the text using the abstract format of the intended publication or a structured summary such as: background, local problem, methods, interventions, results, conclusions	3 - 4
Introduction	*Why did you start?*	
3. Problem Description	Nature and significance of the local problem	5
4. Available knowledge	Summary of what is currently known about the problem, including relevant previous studies	6 - 7

5. Rationale	Informal or formal frameworks, models, concepts, and/or theories used to explain the problem, any reasons or assumptions that were used to develop the intervention(s), and reasons why the intervention(s) was expected to work	7
6. Specific aims	Purpose of the project and of this report	7
Methods	*What did you do?*	
7. Context	Contextual elements considered important at the outset of introducing the intervention(s)	8
8. Intervention(s)	a. Description of the intervention(s) in sufficient detail that others could reproduce it b. Specifics of the team involved in the work	9 - 10
9. Study of the Intervention(s)	a. Approach chosen for assessing the impact of the intervention(s) b. Approach used to establish whether the observed outcomes were due to the intervention(s)	9 - 10
10. Measures	a. Measures chosen for studying processes and outcomes of the intervention(s), including rationale for choosing them, their operational definitions, and their validity and reliability b. Description of the approach to the ongoing assessment of contextual elements that contributed to the success, failure, efficiency, and cost c. Methods employed for assessing completeness and accuracy of data	9
11. Analysis	a. Qualitative and quantitative methods used to draw inferences from the data b. Methods for understanding variation within the data, including the effects of time as a variable	10
12. Ethical Considerations	Ethical aspects of implementing and studying the intervention(s) and how they were addressed, including, but not limited to, formal ethics review and potential conflict(s) of interest	10
Results	*What did you find?*	
13. Results	a. Initial steps of the intervention(s) and their evolution over time (*e.g.*, time-line diagram, flow chart, or table), including modifications made to the intervention during the project b. Details of the process measures and outcome c. Contextual elements that interacted with the intervention(s) d. Observed associations between outcomes, interventions, and relevant contextual elements e. Unintended consequences such as unexpected benefits, problems, failures, or costs associated with the intervention(s). f. Details about missing data	11 -12
Discussion	*What does it mean?*	
14. Summary	a. Key findings, including relevance to the rationale and specific aims b. Particular strengths of the project	13

15. Interpretation	a. Nature of the association between the intervention(s) and the outcomes b. Comparison of results with findings from other publications c. Impact of the project on people and systems d. Reasons for any differences between observed and anticipated outcomes, including the influence of context e. Costs and strategic trade-offs, including opportunity costs	13 - 15
16. Limitations	a. Limits to the generalizability of the work b. Factors that might have limited internal validity such as confounding, bias, or imprecision in the design, methods, measurement, or analysis c. Efforts made to minimize and adjust for limitations	15 - 16
17. Conclusions	a. Usefulness of the work b. Sustainability c. Potential for spread to other contexts d. Implications for practice and for further study in the field e. Suggested next steps	16 - 17
Other information		
18. Funding	Sources of funding that supported this work. Role, if any, of the funding organization in the design, implementation, interpretation, and reporting	17

Table 2. Glossary of key terms used in SQUIRE 2.0. This Glossary provides the intended meaning of selected words and phrases as they are used in the SQUIRE 2.0 Guidelines. They may, and often do, have different meanings in other disciplines, situations, and settings.

Assumptions
Reasons for choosing the activities and tools used to bring about changes in healthcare services at the system level.

Context
Physical and sociocultural makeup of the local environment (for example, external environmental factors, organizational dynamics, collaboration, resources, leadership, and the like), and the interpretation of these factors ("sense-making") by the healthcare delivery professionals, patients, and caregivers that can affect the effectiveness and generalizability of intervention(s).

Ethical aspects
The value of system-level initiatives relative to their potential for harm, burden, and cost to the stakeholders. Potential harms particularly associated with efforts to improve the quality, safety, and value of healthcare services include opportunity costs, invasion of privacy, and staff distress resulting from disclosure of poor performance.

Generalizability
The likelihood that the intervention(s) in a particular report would produce similar results in other settings, situations, or environments (also referred to as external validity).

Healthcare improvement
Any systematic effort intended to raise the quality, safety, and value of healthcare services, usually done at the system level. We encourage the use of this phrase rather than "quality improvement," which often refers to more narrowly defined approaches.

Inferences
The meaning of findings or data, as interpreted by the stakeholders in healthcare services – improvers, healthcare delivery professionals, and/or patients and families

Initiative
A broad term that can refer to organization-wide programs, narrowly focused projects, or the details of specific interventions (for example, planning, execution, and assessment)

Internal validity
Demonstrable, credible evidence for efficacy (meaningful impact or change) resulting from introduction of a specific intervention into a particular healthcare system.

Intervention(s)
The specific activities and tools introduced into a healthcare system with the aim of changing its performance for the better. Complete description of an intervention includes its inputs, internal activities, and outputs (in the form of a logic model, for example), and the mechanism(s) by which these components are expected to produce changes in a system's performance.

Opportunity costs

Loss of the ability to perform other tasks or meet other responsibilities resulting from the diversion of resources needed to introduce, test, or sustain a particular improvement initiative

Problem
Meaningful disruption, failure, inadequacy, distress, confusion or other dysfunction in a healthcare service delivery system that adversely affects patients, staff, or the system as a whole, or that prevents care from reaching its full potential

Process
The routines and other activities through which healthcare services are delivered

Rationale
Explanation of why particular intervention(s) were chosen and why it was expected to work, be sustainable, and be replicable elsewhere.

Systems
The interrelated structures, people, processes, and activities that together create healthcare services for and with individual patients and populations. For example, systems exist from the personal self-care system of a patient, to the individual provider-patient dyad system, to the microsystem, to the macrosystem, and all the way to the market/social/insurance system. These levels are nested within each other.

Theory or theories
Any "reason-giving" account that asserts causal relationships between variables (causal theory) or that makes sense of an otherwise obscure process or situation (explanatory theory). Theories come in many forms, and serve different purposes in the phases of improvement work. It is important to be explicit and well-founded about any informal and formal theory (or theories) that are used.

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Contact Tracing using Real-Time Location System (RTLS): A Simulation Exercise in a Tertiary Hospital in Singapore

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Contact Tracing using Real-Time Location System (RTLS): A Simulation Exercise in a Tertiary Hospital in Singapore

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Word count: 3295

ABSTRACT

Objective: We aim to assess the effectiveness of contact tracing using RTLS compared to the conventional (EMR) method via an EID outbreak simulation exercise. The aims of the study are: (1) to compare the time taken to perform contact tracing and list of contacts identified for RTLS vs EMR; (2) to compare manpower and manpower-hours required to perform contact tracing for RTLS vs EMR; (3) to extrapolate the cost incurred by RTLS vs EMR.

Design: Prospective case study.

Setting: Sengkang General Hospital (SKH), a 1000-bedded public tertiary hospital in Singapore.

Participants: Hospital staff.

Interventions: A simulation exercise to determine and compare the list of contacts, time taken, manpower, and manpower-hours required between RTLS and conventional methods of contact tracing. Cost of both methods were compared.

Primary and Secondary Outcome Measures: List of contacts, time taken, manpower required, manpower-hours required, and cost incurred.

Results: RTLS identified almost three times the number of contacts compared to conventional methods, while achieving that with a 96.2% reduction in time taken, 97.6% reduction in manpower required, and 97.5% reduction in manpower-hours required. However, RTLS incurred significant equipment cost and might take many contact tracing episodes before providing economic benefit.

Conclusion: Albeit costly, RTLS is effective in contact tracing. RLTS might not be ready at present time to replace conventional methods, but with further refinement, RTLS has the

potential to be the gold standard in contact tracing methods of the future, particularly in the current pandemic.

ARTICLE SUMMARY

Strengths and limitations of this study

Strengths

1. Detailed quantification of contacts identified, and time elapsed/taken by RTLS and EMR

2. Detailed quantification of manpower, manpower hours, manpower cost, equipment cost by both methods

Limitations

1. Lack of gold standard in identifying true contacts, hence unable to calculate sensitivity and specificity

2. Study based on one simulation exercise in one institution

3. Impact & cost savings of halting disease transmission earlier not studied

INTRODUCTION

Densely populated metropolitan cities like Singapore receiving high volumes of international visitors are highly susceptible to emerging infectious disease (EID) outbreaks as evident by the recent COVID-19 pandemic. As such, Singapore needs to continually strengthen its defences against EID outbreaks[1]. Founded on the experiences of previous outbreaks, Singapore took a "whole-of-government approach" towards implementing pandemic control measures[2]. To test these measures, the Ministry of Health (MOH) requires all public hospitals to participate every two years in a national simulation exercise[1,3], and be validated in the management of an infectious disease case. A key assessment criterion of the exercise is contact tracing.

Contact tracing, a systematic process of identification, assessment, and management of people exposed to the disease, is a critical element in containing any outbreak[4]. Current methods of contact tracing involve retrospective review of multiple databases, such as electronic medical records (EMR) entered by healthcare workers, hospital registration systems capturing patient journeys in the hospital, and visitor management systems capturing registered visitors to the hospital. After a preliminary list of potential exposures, also known as contacts, is compiled, individual interviews are carried out to identify any other contacts that were not included by the above systems. These conventional methods are time consuming, heavily manpower dependent, and fail to capture a significant number of contacts[5]. This is because the databases used were not primarily designed to identify contacts between individuals[6] and do not provide enough detail to accurately derive a list of contacts. Failure to trace contacts in a timely and accurate manner can lead to continued transmission of diseases, preventing effective control of EID outbreaks.

Radio frequency identification (RFID) technology, which involves fixed readers receiving signals from small ID tags[7], is widely used in many industries such as commerce and logistics. Tagged items can be identified, tracked and managed in real-time through a centralised database and a compatible device[7]. RFID technology is increasingly being adopted for many uses in healthcare settings such as asset and equipment tracking, staff and patient identification, sensing, intervention, and alerts and triggers[8]. These applications provide improvement in patient safety, reduction in medical errors, time and cost savings and improved medical processes[8]. Another potential application of the RFID technology is a real-time location system (RTLS) allowing tracking of interactions among individuals[5]. The use of RTLS in the inference of contact history between healthcare staff and patients has been studied and validated. The National Centre for Infectious Disease (NCID) in Singapore found that RTLS had a sensitivity of 72.2% and a specificity of 87.7%[9]. An intensive care unit in Taiwan found that RTLS had a sensitivity of 81.4%, specificity of 78.8%, and accuracy of 80.7%[6]. An emergency department in the United States fount that RTLS doubled the number of contacts identified compared with EMR review[5].

To date, few studies have evaluated the manpower and economic impact of contact tracing using RTLS compared to conventional methods. RTLS has been found to be an accurate and effective way to perform contact tracing. However, little is known as to whether the accuracy and efficacy of RTLS provides any manpower and monetary cost savings.

In this study, we aim to assess the effectiveness of contact tracing using RTLS compared to the conventional (EMR) method via an EID outbreak simulation exercise in Sengkang General Hospital, Singapore. The aims of the study are:

1. To compare the time taken to perform contact tracing and list of contacts identified for RTLS vs EMR.
2. To compare manpower and manpower-hours required to perform contact tracing for RTLS vs EMR.
3. To extrapolate the cost incurred by RTLS vs EMR.

We hypothesised that contact tracing using RTLS would allow us to identify contacts in a timelier and more accurate fashion. We also hypothesized that contact tracing using RTLS would confer benefits in manpower and manpower-hours reduction, translating to cost savings for the hospital.

MATERIALS AND METHODS

Context

This study was held in Sengkang General Hospital (SKH), a 1000-bedded public acute hospital in Singapore with a staff of 4000. This study was conducted in Feb 2019, at a point when SKH was receiving 3149 admissions and 8172 emergency department visits per month. The study was conducted during the biennial national simulation exercise on EID outbreaks. In this exercise, a surgical patient with a three-day inpatient stay was selected as the simulated MERS-CoV index case. This patient was admitted through the emergency department, underwent surgery in the operating theatre on Day 1, and spent three days in an inpatient ward.

Equipment

The RTLS used for contact tracing in our hospital was based on SmartSense Solutions infrastructure and SmartSense RTLS platform provided by Cadi Scientific[10]. Staff tags and patient tags were deployed. The staff tags were additionally equipped with an antenna that captured tag interactions within a two-metre radius of itself. Tag signals were picked up by the campus-wide network of in-ceiling wireless receivers and exciters. Our RTLS was tested and operational prior to the data collection. As a pilot study, 1000 out of 4000 staff wore staff tags. The selected 1000 staff included doctors and nurses working in high risks areas such as the Emergency Department and the inpatient wards. The rest of the staff, including the remaining doctors, nurses, allied health professionals, ancillary staff, and students were not equipped with staff tags. All patients wore patient tags from registration to discharge. Our RTLS platform captured two forms of contact: (1) tag-to-tag based, and (2) location based. A tag-to-tag based contact was registered when any tags (staff or patient) were detected within a two-metre radius of a staff tag for at least a one-minute duration. A location based contact was registered when any tags were detected within the same location for at least a one-minute duration. Location of tags were determined via WiFi triangulation and chokepoint tracking[7,11].

Measures

A prospective case study was conducted during the biennial national simulation exercise in Sengkang General Hospital on 28 Feb 2019 to determine the list of contacts, time taken, manpower required, and manpower-hours required to perform contact tracing via both RTLS and the conventional method of databases review (EMR). The date of the exercise was unannounced, with the contact tracing team activated only at the point of the exercise itself. All staff involved in contact tracing were briefed prior to the exercise to record the amount of time spent on performing the work of contact tracing.

Intervention

During the simulation exercise, two concurrent contact tracing team performed contact tracing, one via conventional method (EMR), and the other via RTLS. The hospital contact tracing team, which comprised nurse leadership in coordination with hospital infection control, performed contact tracing via conventional methods as per existing hospital contact tracing protocol. Firstly, an activity map of the index case, comprising the journey within the hospital, was derived after reviewing the EMR. Subsequently, a list of contacts comprising healthcare workers, other patients, and hospital visitors, was compiled via various databases. The EMR identified any healthcare workers who documented their interactions with the patient, the hospital registration system identified other patients who were in the same location as the index case, and the visitor management system identified visitors who registered to visit the location of the index case.

Concurrently, the other team generated the activity map and the list of contacts using the RTLS platform. The activity map showed the entire journey within the hospital, depicting each

location and the duration the index case visited. The list of contacts was then derived for each of these locations, depicting the time and duration of each staff and patient the index case came in contact with.

Analysis

Between the two methods used for contact tracing, we compared the time taken, manpower required, manpower-hours required, and the list of contacts identified. Between the two contact lists, we compared the number of contacts, and the roles of these contacts (doctors, nurses, allied health workers, ancillary staff, patients, or visitors). As a significant proportion of the existing staff were not equipped with the staff tags at that point of the study, the comparison between the lists was done primarily on staff equipped with the tags. Descriptive statistics were used to compare the two methods.

Patient and Public Involvement

It was not appropriate or possible to involve patients or the public in the design, or conduct, or reporting, or dissemination plans of our research.

Ethical Considerations

This study was reviewed and approved byThis study involves human participants but the SingHealth Centralised Institutional Review Board (CIRB) exempted this study. CIRB Ref: 2018/3093

RESULTS

Simulation Exercise

The index case had a length of stay of three days and seven minutes and visited three main locations in the hospital: emergency department, operating theatre, and inpatient ward. RTLS identified 226 unique contacts, of which there were 157 staff and 69 patients. EMR identified 288 unique contacts, of which 82 (27 staff and 55 patients) were tagged (Table 1). For a better comparison of results, untagged staff were excluded, and subsequent comparisons were made using only tagged staff and patients.

Out of a total of 260 unique contacts, RTLS identified 226 while EMR (tagged) identified 82, with an overlap of 48 (Table 2 & Figure 1). RTLS yielded an additional 178 contacts over the 82 contacts EMR (tagged) yielded, giving an additional 217.1% unique contacts. Out of all the unique contacts, RTLS detected 86.9% while EMR detected 31.5%.

The comparison is further broken down into the three locations visited by the index case, namely the emergency department (ED), the operating theatre (OT) and the inpatient ward. RTLS yielded the highest increase of 263.3% in unique contacts in the ward, and lowest increase of 66.7% in the OT (Table 2 & Figure 1). Interestingly, RTLS yielded an increase of 870.0% unique staff contacts over EMR in the ED.

Comparing the time taken, manpower, and manpower-hours required, RTLS took 0.9h, 1 manpower, and 0.9 manpower-hours while EMR took 23.7h, 42 manpower, and 35.3 manpower-hours (Table 3). RTLS provided a 96.2% reduction in time taken, 97.6% reduction in manpower, and 97.5% reduction in manpower-hours required. By RTLS, only one staff was required to acquire the activity map and contact list. Conversely, by EMR, two staff from the infection control department were needed to lead the contact tracing efforts, involving 24 additional departments and 40 other staff in the process.

In terms of hospital costs, RTLS required an equipment cost (RTLS platform and staff tags) of $653,594 for the first three years to purchase and maintain the system, whereas EMR method required no additional equipment cost. In terms of manpower costs computed over the simulation exercise, RTLS method incurred a manpower cost of $62 per contact tracing episode, whereas EMR method incurred a manpower cost of $2,125. We computed the expected expenditure over three years to evaluate the long-term cost between RTLS and EMR, as the staff tags had an estimated lifespan of three years. We found that at least 317 contact tracing episodes were needed in the three-year period to obtain cost benefit for RTLS (Table 4).

DISCUSSION

Summary

Overall, RTLS identified almost three times the number of contacts compared to EMR, while achieving that with significantly less time, manpower, manpower-hours, and manpower cost. One caveat to RTLS that may be prohibitive to its implementation is its high cost of entry as the equipment cost incurred can be significant and might take many contact tracing episodes to occur before providing economic benefit.

Interpretation

Similar to the study in Mayo Clinic [5], our study found that RTLS identified more contacts than EMR. Interestingly, RTLS identified an unproportionally large increase of unique contacts in the ED, which was later discovered to be false positive due to off-duty staff keeping their tags in ED lockers. The other RTLS contacts within the ED, the OT, and the ward were found to otherwise be largely accurate. They were identified by RTLS but not EMR for reasons such as doctors and nurses reviewing patients other than the index case, but physically within proximity to the index case. RTLS also detected nurses who chaperoned patients other than the index case to the OT and came in proximity to the index case. Other instances found patients who were physically within the ED as detected by RTLS but omitted by EMR as they were logged as already "discharged" within the EMR system. The value proposition of the RTLS is its capability in detecting such contacts which would otherwise be difficult to establish in the current systems.

The study in Taiwan and Singapore found RTLS to have good sensitivity, specificity and accuracy[6,9]. In our study, RTLS proved to be effective in the identification of contacts as it possibly has better sensitivity than EMR as shown by the identification of contacts that went undetected by EMR, and better specificity by showing some contacts detected by EMR to be false positives due to the subdivision of locations in the RTLS platform. However, non-compliance to tag charging and wearing proved to limit the effectiveness of RTLS. To circumvent such limitations, more staff education and training can be implemented to emphasize the appropriate usage of staff tags. Future tags designs could also be integrated into existing staff cards, which are required for staff to gain access into hospital compound and staff-restricted areas within the campus, thus resolving some of the compliance issues faced in this study.

During the COVID pandemic, Singapore deployed a Bluetooth-based contact tracing app TraceTogether to augment contact tracing capabilities[10]. A validation study comparing the Bluetooth-based app against RTLS by the National Centre for Infectious Disease (NCID) in Singapore found that RTLS has a sensitivity of 95.3% as compared to 6.5% for the Bluetooth-based TraceTogether app[12], suggesting RTLS to be a more effective contact tracing tool in the hospital setting. Despite the better sensitivity, there is still a role for Bluetooth-based contact tracing apps in the community as RTLS would be challenging to implement.

Since the start of COVID-19 till now, much has evolved on the understanding of the disease transmission. It is now known that COVID-19 spread primarily via oral and respiratory aerosols, as compared to large respiratory droplets contaminated with the virus as initially believed[13,14]. Although RTLS does not possess the fidelity to differentiate between low-risk and high-risk clinical activities, we were able to define RTLS contacts based on the duration of exposure (defined at 1min in our study). This can also be redefined based on the transmissibility of the specific disease with each subsequent contact tracing episodes.

Aligned with the study in Mayo Clinic that estimated RTLS to take <5 minutes while EMR to take 30-60 minutes[5], our study found RTLS provided significant time, manpower, and manpower-hour savings. RTLS can consistently deliver similar results regardless of the index case's length of stay, number of locations visited, number of departments involved (e.g. allied health professionals' involvement), or day of contact tracing (weekday vs weekend). Although not specifically measured, contact tracing was swiftly and effectively performed with our RTLS system for 1401 COVID-10 patients in our institution within the first seven months of the COVID-19 pandemic[10]. With EMR, anecdotal evidence revealed that longer lengths of stay, larger numbers of locations visited, larger numbers of departments involved, as well as contact tracing over a weekend can all result in significant delays in contact tracings. Moreover, should all staff in the hospital be tagged, the objective data provided by RTLS would reduce the subsequent work of verification and interview with each contact. Perhaps, the RTLS platform can also be designed to coordinate with other hospital communication systems to trigger automated text messages or emails to be sent to the affected individuals, further reducing the downstream workload of the contact tracing team.

Our cost computations found that initial investment on the RTLS equipment can prove to be costly and present a significant barrier to entry, requiring about two contact tracing episodes per week for RTLS to warrant the investment, while an average of two contact tracing episodes occurred monthly in our hospital (pre-COVID). It is found in other studies that RTLS can be justified in large urban healthcare institutions with diverse patient populations, but not so in small community healthcare institutions[5]. Further studies are required to evaluate and justify the cost of RTLS in Singapore. Alternatively, future studies can look into the cost-benefit analysis of tagging certain groups of the healthcare staff over the others, hence lowering the equipment cost of RTLS.

Privacy concerns can pose significant barrier to adoption and compliance to RTLS tags[12,15]. For privacy reasons, the RTLS data collected is only within the hospital compound and is only stored for a required period (currently set at 3 months). The data obtained retrieved solely for the purposes of contact tracing and is only available to authorised personnel tasked to perform contact tracing work in the hospital.

Limitations

The results of our study are based on one simulation exercise in our institution, hence limiting generalisability. Factors such as index case length of stay, number of locations visited, number of departments involved, or the day contact tracing was performed could all influence the results and necessitate further investigations. Despite the absence of any prior notice, the simulation exercise was held within a month of two prior rehearsals. As such, heightened sense of awareness among hospital staff that an exercise was about to occur, coupled with a possible Hawthorne effect of a simulation exercise, could have resulted in shorter than usual response time. As contacts of the index case were not observed prior to contact tracing, there were no definitive means of determining the true positives and negatives of both methods, though the RTLS was tested and deemed operational prior to the data collection. Also, only 1000 permanent staff deemed working in high-risk areas were tagged. However, our EMR contacts revealed significant untagged populations such as junior doctors on six-month rotations, allied health professions, and ancillary staff providing meals, cleaning, and porter services. These groups of people were under-represented in this study and their inclusion may result in different contact activities.

Early recognition and mitigation of an EID is paramount in impeding the multiplicative effect of any outbreak, potentially limiting its transmission towards a widespread epidemic. Other studies showed contact tracing to be critical in halting disease transmission[16], and further studies possibly with computational models can more accurately show the clinical benefits conferred by performing contact tracing with RTLS.

Current cost computations consist of only equipment and manpower costs, without considerations on the economic impact of reducing disease transmission. Future studies taking into account the economic impact of reducing disease transmission, particularly in COVID-19, might show RTLS to confer greater economic benefits than presented in this study.

Conclusion

Compared to EMR, we found that RTLS identified contacts in a timelier and more accurate fashion, required fewer manpower and manpower-hours, and has the potential to limit disease transmission. Despite the advantages, high equipment cost is incurred with RTLS and might present significant barrier to adoption. RLTS might be at a nascent stage and not be ready to completely replace conventional methods in contact tracing. However, with subsequent cycles of plan-do-study-act (PDSA)[17] and further studies taking into account the economic impact of reducing disease transmission, RTLS has the potential to be the gold standard in contact tracing methods of the future.

This study explicitly examines the time, manpower, manpower-hours, reduction in disease transmission, and cost of performing contact tracing between RTLS and other conventional means. Our findings hold implications for hospital administrators and healthcare regulators, especially within the country, to relook at how existing standards of contact tracing can be improved.

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AUTHOR CONTRIBUTION

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- Substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data for the work; AND
- Drafting the work or revising it critically for important intellectual content; AND
- Final approval of the version to be published; AND
- Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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- Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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TABLES

Table 1 Comparison of contact list breakdown identified by real-time location system (RTLS) and electronic medical record (EMR). Table created by authors.

Role	RTLS	EMR		
		Tagged	Untagged	Total
Healthcare Workers	157	27	110	137
- Doctors	*8*	*2*	*39*	*41*
- Nurses	*149*	*25*	*19*	*44*
- Allied Health Professionals	*0*	*0*	*11*	*11*
- Ancillary Staff	*0*	*0*	*41*	*41*
Patients	69	55	0	55
Visitors	0	0	96	96
Total	226	82	206	288

Table 2 Comparison of contact list between RTLS and EMR (Tagged) by role only, and by location/role. Table created by authors.

Role	RTLS	EMR (Tagged)	RTLS (but not EMR)	Both RTLS & EMR	EMR (but not RTLS)	Total unique contacts	RTLS increase over EMR (%)
Healthcare Workers	157	27	136	21	6	163	503.7
- Doctors	*8*	*2*	*7*	*1*	*1*	*9*	*350.0*
- Nurses	*149*	*25*	*129*	*20*	*5*	*154*	*516.0*
Patients	69	55	42	27	28	97	76.4
Total	226	82	178	48	34	260	217.1
[a] Detection rate (%)	86.9	31.5				100	175.6
Location / Role	**RTLS**	**EMR (Tagged)**	**RTLS (but not EMR)**	**Both RTLS & EMR**	**EMR (but not RTLS)**	**Total unique contacts**	**RTLS increase over EMR (%)**
Emergency Department	114	47	90	24	23	137	191.5
- Staff (doctors & nurses)	*94*	*10*	*87*	*7*	*3*	*97*	*870.0*
- Patients	*20*	*37*	*3*	*17*	*20*	*40*	*8.1*
Operating Theatre	12	9	6	6	3	15	66.7
- Staff (doctors & nurses)	*5*	*1*	*4*	*1*	*0*	*5*	*400.0*
- Patients	*7*	*8*	*2*	*5*	*3*	*10*	*25.0*
Ward (Inpatient)	101	30	79	22	8	109	263.3
- Staff (doctors & nurses)	*54*	*16*	*41*	*13*	*3*	*57*	*256.3*
- Patients	*47*	*14*	*38*	*9*	*5*	*52*	*271.4*

*[a] Detection rate = [(Contacts detected by either methods)/(Total unique contacts)]*100%*

Table 3 Comparison of time taken, manpower required, and manpower-hours required between RTLS and EMR. Table created by authors.

RTLS				EMR			
Process	**[a] Elapsed time (h)**	**[b] Manpower required**	**Manpower-hours required (h)**	**Process**	**[a] Elapsed time (h)**	**[b] Manpower required**	**Manpower-hours required (h)**
Index case identified	0	0	0.0	Index case identified	0	0	0.0
Activity map: Generate activity map via SmartSense	0.1	1	0.1	Activity map: SAP check (hospital registration system)	0.1	1	0.1
				Activity map: Contact OT (OT journey)	0.5	1	0.4
				Activity map: SCM check (EMR)	0.6	1	0.6
				Activity map: Contact ED (ED journey)	0.8	1	0.3
Activity map: Sort data and fill of MOH activity map template	0.5	1	0.4	Activity map: Verify data and fill of MOH activity map template	1.5	2	0.8
Contact list: Generate contact list via SmartSense	0.6	1	0.1	Contact list: Contact MI (list of exposed patients)	1.7	1	0.2
				Contact list: Email all stakeholders - ED, OT, Ward, AHP (13dept), Anc staff (5dept)	1.9	1	1.1
				Contact list: Contact AVMS (list of exposed visitors)	2.2	2	0.4
				Contact list: Sort MI data (list of exposed patients)	3.9	1	0.2
				Contact list: Contact IHIS (author list of EMR)	4	1	0.2
				Contact list: Sort IHIS data (author list of EMR)	7.2	1	0.5
Contact list: Review and sort contact tracing data, and fill MOH contact list template	0.9	1	0.3	Contact list: Compile data, call and clarify non-response / missing data, and fill MOH contact list template	23.7	2	12.0
	[a] 0.9	[b] 1	0.9		[a] 23.7	[b] 2	16.4
Downstream Departments		**Manpower required**	**Manpower-hours required (h)**	**Downstream Departments**		**Manpower required**	**Manpower-hours required (h)**
None		0	0.0	Emergency Department		1	1.3
				Operating Theatre		1	1.0
				Ward 19		1	1.0
				Management Information - eHints		1	0.5
				AVMS dept		4	2.5
				Integrated Health Information Systems		2	1.5
				Audiology		1	0.2
				Clinical Measurement Centre		1	0.1
				Dietetics		1	0.1
				Medical Social Services		1	0.2

		0	0.0
	[a] Elapsed time (h)	[b] Manpower required	Manpower-hours required (h)
Total	**[a] 0.9**	**[b] 1**	**0.9**
Decrease over EMR (%)	**96.2**	**97.6**	**97.5**

Occupational Therapy		1	0.3
Pathology		1	0.1
Pharmacy		2	0.7
Physiotherapy		3	1.2
Podiatry		2	0.5
Psychology		1	0.3
Radiology		1	0.5
Respiratory Therapy		1	0.8
Speech Therapy		1	0.2
Environmental Services		6	1.8
Facilities Management & Engineering		1	2.0
General Services		2	1.2
Materials Management		1	0.8
Security		3	0.3
		40	18.9
	[a] Elapsed time (h)	[b] Manpower required	Manpower-hours required (h)
Total	**[a] 23.7**	**[b] 42**	**35.3**

[a] Elapsed time refers to the amount of time that has passed since the start of the exercise at the point of completion of a process, hence the total elapsed time is not a simple sum of the above cells.
[b] Manpower required is the number of staff it took to perform the process. Many of the processes were performed by the same staff, and hence the total manpower required is not a simple sum of the above cells.

Table 4 Comparison of cost between RTLS and EMR. Table created by authors.

Cost	**RTLS**	**EMR**
[a] Equipment cost (for first three years)	$653,594	$0
[b] Manpower cost (for each contact tracing episode)	$62	$2,125
Case scenarios		
36 contact tracing episodes in 3 years	$655,826	$76,500
156 contact tracing episodes in 3 years	$663,266	$331,500
317 contact tracing episodes in 3 years	$673,248	$673,625

[a] Equipment cost (RTLS) = cost of RTLS platform + cost of staff tags
*[b] Manpower cost = (manpower-hours of Staff 1 * norm cost of Staff 1) + (manpower-hours of Staff 2 * norm cost of Staff 2) + … + (manpower-hours of Staff N * norm cost of Staff N)*

FIGURES

Figure 1 Comparison of RTLS vs EMR (tagged) broken down into: (a) total - staff & patients, (b) total - staff (doctors & nurses), (c) total - patients, (d) ED - staff (doctors & nurses), (e) ED - patients, (f) OT - staff (doctors & nurses), (g) OT - patients, (h) Ward - staff (doctors & nurses), and (i) Ward - patients. Figure created by authors.

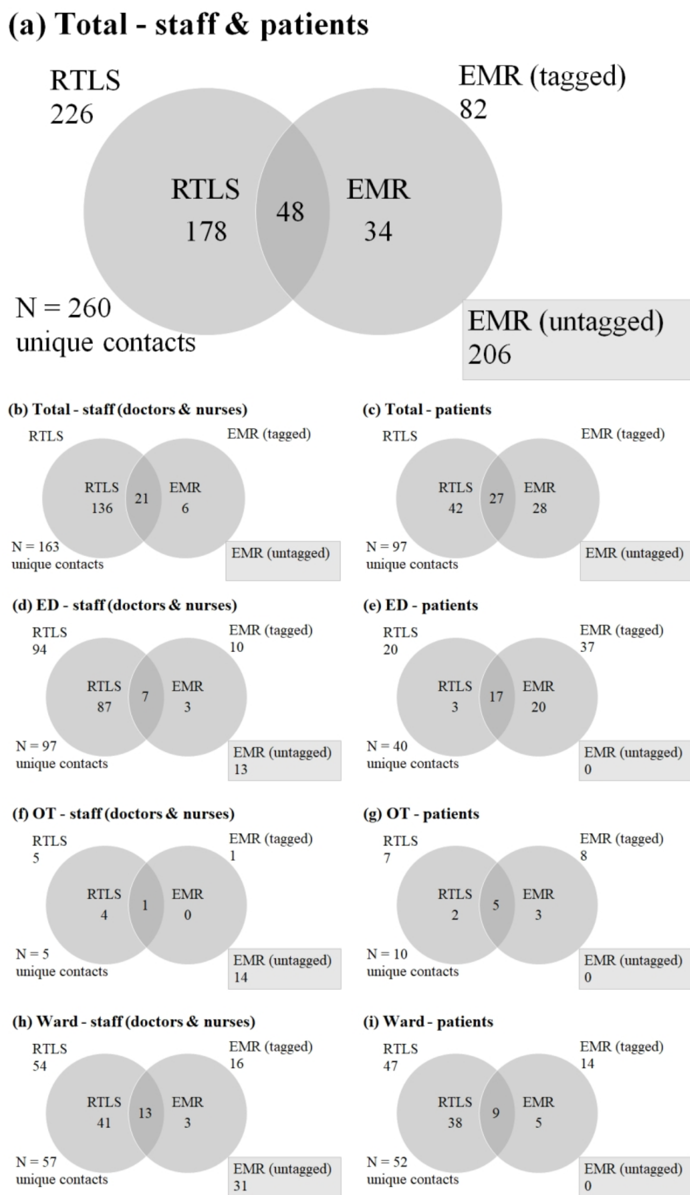

Figure 1 Comparison of RTLS vs EMR (tagged) broken down into: (a) total - staff & patients, (b) total - staff (doctors & nurses), (c) total - patients, (d) ED - staff (doctors & nurses), (e) ED - patients, (f) OT - staff (doctors & nurses), (g) OT - patients, (h) Ward - staff (doctors & nurses), and (i) Ward - patients. Figure created by authors.

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Revised Standards for Quality Improvement Reporting Excellence (SQUIRE 2.0)
September 15, 2015

Text Section and Item Name	Section or Item Description	
Notes to authors	• The SQUIRE guidelines provide a framework for reporting new knowledge about how to improve healthcare • The SQUIRE guidelines are intended for reports that describe system level work to improve the quality, safety, and value of healthcare, and used methods to establish that observed outcomes were due to the intervention(s). • A range of approaches exists for improving healthcare. SQUIRE may be adapted for reporting any of these. • Authors should consider every SQUIRE item, but it may be inappropriate or unnecessary to include every SQUIRE element in a particular manuscript. • The SQUIRE Glossary contains definitions of many of the key words in SQUIRE. • The Explanation and Elaboration document provides specific examples of well-written SQUIRE items, and an in-depth explanation of each item. • Please cite SQUIRE when it is used to write a manuscript.	
Title and Abstract		Page
1. Title	Indicate that the manuscript concerns an initiative to improve healthcare (broadly defined to include the quality, safety, effectiveness, patient-centeredness, timeliness, cost, efficiency, and equity of healthcare)	1
2. Abstract	a. Provide adequate information to aid in searching and indexing b. Summarize all key information from various sections of the text using the abstract format of the intended publication or a structured summary such as: background, local problem, methods, interventions, results, conclusions	3 - 4
Introduction	*Why did you start?*	
3. Problem Description	Nature and significance of the local problem	5
4. Available knowledge	Summary of what is currently known about the problem, including relevant previous studies	6 - 7

5. Rationale	Informal or formal frameworks, models, concepts, and/or theories used to explain the problem, any reasons or assumptions that were used to develop the intervention(s), and reasons why the intervention(s) was expected to work	7
6. Specific aims	Purpose of the project and of this report	7
Methods	*What did you do?*	
7. Context	Contextual elements considered important at the outset of introducing the intervention(s)	8
8. Intervention(s)	a. Description of the intervention(s) in sufficient detail that others could reproduce it b. Specifics of the team involved in the work	9 - 10
9. Study of the Intervention(s)	a. Approach chosen for assessing the impact of the intervention(s) b. Approach used to establish whether the observed outcomes were due to the intervention(s)	9 - 10
10. Measures	a. Measures chosen for studying processes and outcomes of the intervention(s), including rationale for choosing them, their operational definitions, and their validity and reliability b. Description of the approach to the ongoing assessment of contextual elements that contributed to the success, failure, efficiency, and cost c. Methods employed for assessing completeness and accuracy of data	9
11. Analysis	a. Qualitative and quantitative methods used to draw inferences from the data b. Methods for understanding variation within the data, including the effects of time as a variable	10
12. Ethical Considerations	Ethical aspects of implementing and studying the intervention(s) and how they were addressed, including, but not limited to, formal ethics review and potential conflict(s) of interest	10
Results	*What did you find?*	
13. Results	a. Initial steps of the intervention(s) and their evolution over time (*e.g.*, time-line diagram, flow chart, or table), including modifications made to the intervention during the project b. Details of the process measures and outcome c. Contextual elements that interacted with the intervention(s) d. Observed associations between outcomes, interventions, and relevant contextual elements e. Unintended consequences such as unexpected benefits, problems, failures, or costs associated with the intervention(s). f. Details about missing data	11 -12
Discussion	*What does it mean?*	
14. Summary	a. Key findings, including relevance to the rationale and specific aims b. Particular strengths of the project	13

15. Interpretation	a. Nature of the association between the intervention(s) and the outcomes b. Comparison of results with findings from other publications c. Impact of the project on people and systems d. Reasons for any differences between observed and anticipated outcomes, including the influence of context e. Costs and strategic trade-offs, including opportunity costs	13 - 15
16. Limitations	a. Limits to the generalizability of the work b. Factors that might have limited internal validity such as confounding, bias, or imprecision in the design, methods, measurement, or analysis c. Efforts made to minimize and adjust for limitations	15 - 16
17. Conclusions	a. Usefulness of the work b. Sustainability c. Potential for spread to other contexts d. Implications for practice and for further study in the field e. Suggested next steps	16 - 17
Other information		
18. Funding	Sources of funding that supported this work. Role, if any, of the funding organization in the design, implementation, interpretation, and reporting	17

Table 2. Glossary of key terms used in SQUIRE 2.0. This Glossary provides the intended meaning of selected words and phrases as they are used in the SQUIRE 2.0 Guidelines. They may, and often do, have different meanings in other disciplines, situations, and settings.

Assumptions
Reasons for choosing the activities and tools used to bring about changes in healthcare services at the system level.

Context
Physical and sociocultural makeup of the local environment (for example, external environmental factors, organizational dynamics, collaboration, resources, leadership, and the like), and the interpretation of these factors ("sense-making") by the healthcare delivery professionals, patients, and caregivers that can affect the effectiveness and generalizability of intervention(s).

Ethical aspects
The value of system-level initiatives relative to their potential for harm, burden, and cost to the stakeholders. Potential harms particularly associated with efforts to improve the quality, safety, and value of healthcare services include opportunity costs, invasion of privacy, and staff distress resulting from disclosure of poor performance.

Generalizability
The likelihood that the intervention(s) in a particular report would produce similar results in other settings, situations, or environments (also referred to as external validity).

Healthcare improvement
Any systematic effort intended to raise the quality, safety, and value of healthcare services, usually done at the system level. We encourage the use of this phrase rather than "quality improvement," which often refers to more narrowly defined approaches.

Inferences
The meaning of findings or data, as interpreted by the stakeholders in healthcare services – improvers, healthcare delivery professionals, and/or patients and families

Initiative
A broad term that can refer to organization-wide programs, narrowly focused projects, or the details of specific interventions (for example, planning, execution, and assessment)

Internal validity
Demonstrable, credible evidence for efficacy (meaningful impact or change) resulting from introduction of a specific intervention into a particular healthcare system.

Intervention(s)
The specific activities and tools introduced into a healthcare system with the aim of changing its performance for the better. Complete description of an intervention includes its inputs, internal activities, and outputs (in the form of a logic model, for example), and the mechanism(s) by which these components are expected to produce changes in a system's performance.

Opportunity costs

Loss of the ability to perform other tasks or meet other responsibilities resulting from the diversion of resources needed to introduce, test, or sustain a particular improvement initiative

Problem
Meaningful disruption, failure, inadequacy, distress, confusion or other dysfunction in a healthcare service delivery system that adversely affects patients, staff, or the system as a whole, or that prevents care from reaching its full potential

Process
The routines and other activities through which healthcare services are delivered

Rationale
Explanation of why particular intervention(s) were chosen and why it was expected to work, be sustainable, and be replicable elsewhere.

Systems
The interrelated structures, people, processes, and activities that together create healthcare services for and with individual patients and populations. For example, systems exist from the personal self-care system of a patient, to the individual provider-patient dyad system, to the microsystem, to the macrosystem, and all the way to the market/social/insurance system. These levels are nested within each other.

Theory or theories
Any "reason-giving" account that asserts causal relationships between variables (causal theory) or that makes sense of an otherwise obscure process or situation (explanatory theory). Theories come in many forms, and serve different purposes in the phases of improvement work. It is important to be explicit and well-founded about any informal and formal theory (or theories) that are used.

BMJ Open

Contact Tracing using Real-Time Location System (RTLS): A Simulation Exercise in a Tertiary Hospital in Singapore

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Contact Tracing using Real-Time Location System (RTLS): A Simulation Exercise in a Tertiary Hospital in Singapore

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Keywords/phrases: contact tracing; real-time location system (RTLS); communicable disease control; infection control; epidemiology; health policy; health informatics; information technology

Word count: 3298

ABSTRACT

Objective: We aim to assess the effectiveness of contact tracing using real-time location system (RTLS) compared to the conventional (electronic medical records (EMR)) method via an emerging infectious disease (EID) outbreak simulation exercise. The aims of the study are: (1) to compare the time taken to perform contact tracing and list of contacts identified for RTLS vs EMR; (2) to compare manpower and manpower-hours required to perform contact tracing for RTLS vs EMR; (3) to extrapolate the cost incurred by RTLS vs EMR.

Design: Prospective case study.

Setting: Sengkang General Hospital (SKH), a 1000-bedded public tertiary hospital in Singapore.

Participants: 1000 out of 4000 staff wore staff tags in this study.

Interventions: A simulation exercise to determine and compare the list of contacts, time taken, manpower, and manpower-hours required between RTLS and conventional methods of contact tracing. Cost of both methods were compared.

Primary and Secondary Outcome Measures: List of contacts, time taken, manpower required, manpower-hours required, and cost incurred.

Results: RTLS identified almost three times the number of contacts compared to conventional methods, while achieving that with a 96.2% reduction in time taken, 97.6% reduction in manpower required, and 97.5% reduction in manpower-hours required. However, RTLS incurred significant equipment cost and might take many contact tracing episodes before providing economic benefit.

Conclusion: Albeit costly, RTLS is effective in contact tracing. RLTS might not be ready at present time to replace conventional methods, but with further refinement, RTLS has the

potential to be the gold standard in contact tracing methods of the future, particularly in the current pandemic.

ARTICLE SUMMARY

Strengths and limitations of this study

Strengths

1. Detailed quantification of contacts identified, and time elapsed/taken by RTLS and EMR

2. Detailed quantification of manpower, manpower hours, manpower cost, equipment cost by both methods

Limitations

1. Lack of validation study/gold standard in identifying true contacts, hence unable to perform statistical analysis nor calculate sensitivity and specificity

2. Study based on one simulation exercise in one institution

3. Impact & cost savings of halting disease transmission earlier not studied

INTRODUCTION

Densely populated metropolitan cities like Singapore receiving high volumes of international visitors are highly susceptible to emerging infectious disease (EID) outbreaks as evident by the recent coronavirus disease of 2019 (COVID-19) pandemic. As such, Singapore needs to continually strengthen its defences against EID outbreaks[1]. Founded on the experiences of previous outbreaks, Singapore took a "whole-of-government approach" towards implementing pandemic control measures[2]. To test these measures, the Ministry of Health (MOH) requires all public hospitals to participate every two years in a national simulation exercise[1,3], and be validated in the management of an infectious disease case. A key assessment criterion of the exercise is contact tracing.

Contact tracing, a systematic process of identification, assessment, and management of people exposed to the disease, is a critical element in containing any outbreak[4]. Current methods of contact tracing involve retrospective review of multiple databases, such as electronic medical records (EMR) entered by healthcare workers, hospital registration systems capturing patient journeys in the hospital, and visitor management systems capturing registered visitors to the hospital. After a preliminary list of potential exposures, also known as contacts, is compiled, individual interviews are carried out to identify any other contacts that were not included by the above systems. These conventional methods are time consuming, heavily manpower dependent, and fail to capture a significant number of contacts[5]. This is because the databases used were not primarily designed to identify contacts between individuals[6] and do not provide enough detail to accurately derive a list of contacts. Failure to trace contacts in a timely and accurate manner can lead to continued transmission of diseases, preventing effective control of EID outbreaks.

Radio frequency identification (RFID) technology, which involves fixed readers receiving signals from small ID tags[7], is widely used in many industries such as commerce and logistics.

Tagged items can be identified, tracked and managed in real-time through a centralised database and a compatible device[7]. RFID technology is increasingly being adopted for many uses in healthcare settings such as asset and equipment tracking, staff and patient identification, sensing, intervention, and alerts and triggers[8]. These applications provide improvement in patient safety, reduction in medical errors, time and cost savings and improved medical processes[8]. Another potential application of the RFID technology is a real-time location system (RTLS) allowing tracking of interactions among individuals[5]. The use of RTLS in the inference of contact history between healthcare staff and patients has been studied and validated. The National Centre for Infectious Disease (NCID) in Singapore found that RTLS had a sensitivity of 72.2% and a specificity of 87.7%[9]. An intensive care unit in Taiwan found that RTLS had a sensitivity of 81.4%, specificity of 78.8%, and accuracy of 80.7%[6]. An emergency department in the United States fount that RTLS doubled the number of contacts identified compared with EMR review[5].

To date, few studies have evaluated the manpower and economic impact of contact tracing using RTLS compared to conventional methods. RTLS has been found to be an accurate and effective way to perform contact tracing. However, little is known as to whether the accuracy and efficacy of RTLS provides any manpower and monetary cost savings.

In this study, we aim to assess the effectiveness of contact tracing using RTLS compared to the conventional (EMR) method via an EID outbreak simulation exercise in Sengkang General Hospital, Singapore. The aims of the study are:

1. To compare the time taken to perform contact tracing and list of contacts identified for RTLS vs EMR.
2. To compare manpower and manpower-hours required to perform contact tracing for RTLS vs EMR.

3. To extrapolate the cost incurred by RTLS vs EMR.

We hypothesised that contact tracing using RTLS would allow us to identify contacts in a timelier and more accurate fashion. We also hypothesized that contact tracing using RTLS would confer benefits in manpower and manpower-hours reduction, translating to cost savings for the hospital.

MATERIALS AND METHODS

Context

This study was held in Sengkang General Hospital (SKH), a 1000-bedded public acute hospital in Singapore with a staff of 4000. This study was conducted in Feb 2019, at a point when SKH was receiving 3149 admissions and 8172 emergency department visits per month. The study was conducted during the biennial national simulation exercise on EID outbreaks. In this exercise, a surgical patient with a three-day inpatient stay was selected as the simulated Middle East Respiratory Coronavirus (MERS-CoV) index case. This patient was admitted through the emergency department, underwent surgery in the operating theatre on Day 1, and spent three days in an inpatient ward.

Equipment

The RTLS used for contact tracing in our hospital was based on SmartSense Solutions infrastructure and SmartSense RTLS platform provided by Cadi Scientific[10]. Staff tags and patient tags were deployed. The staff tags were additionally equipped with an antenna that captured tag interactions within a two-metre radius of itself. Tag signals were picked up by the campus-wide network of in-ceiling wireless receivers and exciters. Our RTLS was tested and operational prior to the data collection. In this study, 1000 out of 4000 staff wore staff tags. The selected 1000 staff included doctors and nurses working in high risks areas such as the Emergency Department and the inpatient wards. The rest of the staff, including the remaining doctors, nurses, allied health professionals, ancillary staff, and students were not equipped with staff tags. All patients wore patient tags from registration to discharge. Our RTLS platform captured two forms of contact: (1) tag-to-tag based, and (2) location based. A tag-to-tag based contact was registered when any tags (staff or patient) were detected within a two-metre radius of a staff tag for at least a one-minute duration. A location based contact was registered when any tags were detected within the same location for at least a one-minute duration. Location of tags were determined via WiFi triangulation and chokepoint tracking[7,11].

Measures

A prospective case study was conducted during the biennial national simulation exercise in Sengkang General Hospital on 28 Feb 2019 to determine the list of contacts, time taken, manpower required, and manpower-hours required to perform contact tracing via both RTLS and the conventional method of databases review (EMR). The date of the exercise was unannounced, with the contact tracing team activated only at the point of the exercise itself. All staff involved in contact tracing were briefed prior to the exercise to record the amount of time spent on performing the work of contact tracing.

Intervention

During the simulation exercise, two concurrent contact tracing team performed contact tracing, one via conventional method (EMR), and the other via RTLS. The hospital contact tracing team, which comprised nurse leadership in coordination with hospital infection control, performed contact tracing via conventional methods as per existing hospital contact tracing protocol. Firstly, an activity map of the index case, comprising the journey within the hospital, was derived after reviewing the EMR. Subsequently, a list of contacts comprising healthcare workers, other patients, and hospital visitors, was compiled via various databases. The EMR identified any healthcare workers who documented their interactions with the patient, the hospital registration system identified other patients who were in the same location as the index case, and the visitor management system identified visitors who registered to visit the location of the index case.

Concurrently, the other team generated the activity map and the list of contacts using the RTLS platform. The activity map showed the entire journey within the hospital, depicting each

location and the duration the index case visited. The list of contacts was then derived for each of these locations, depicting the time and duration of each staff and patient the index case came in contact with.

Analysis

Between the two methods used for contact tracing, we compared the time taken, manpower required, manpower-hours required, and the list of contacts identified. Between the two contact lists, we compared the number of contacts, and the roles of these contacts (doctors, nurses, allied health workers, ancillary staff, patients, or visitors). As a significant proportion of the existing staff were not equipped with the staff tags at that point of the study, the comparison between the lists was done primarily on staff equipped with the tags. Descriptive statistics were used to compare the two methods.

Patient and Public Involvement

It was not appropriate or possible to involve patients or the public in the design, or conduct, or reporting, or dissemination plans of our research.

Ethical Considerations

This study involves human participants, but the SingHealth Centralised Institutional Review Board (CIRB) reviewed and exempted this study. CIRB Ref: 2018/3093

RESULTS

Simulation Exercise

The index case had a length of stay of three days and seven minutes and visited three main locations in the hospital: emergency department, operating theatre, and inpatient ward. RTLS identified 226 unique contacts, of which there were 157 staff and 69 patients. EMR identified 288 unique contacts, of which 82 (27 staff and 55 patients) were tagged (Table 1). For a better comparison of results, untagged staff were excluded, and subsequent comparisons were made using only tagged staff and patients.

Out of a total of 260 unique contacts, RTLS identified 226 while EMR (tagged) identified 82, with an overlap of 48 (Table 2 & Figure 1). RTLS yielded an additional 178 contacts over the 82 contacts EMR (tagged) yielded, giving an additional 217.1% unique contacts. Out of all the unique contacts, RTLS detected 86.9% while EMR detected 31.5%.

The comparison is further broken down into the three locations visited by the index case, namely the emergency department (ED), the operating theatre (OT) and the inpatient ward. RTLS yielded the highest increase of 263.3% in unique contacts in the ward, and lowest increase of 66.7% in the OT (Table 2 & Figure 1). Interestingly, RTLS yielded an increase of 870.0% unique staff contacts over EMR in the ED.

Comparing the time taken, manpower, and manpower-hours required, RTLS took 0.9h, 1 manpower, and 0.9 manpower-hours while EMR took 23.7h, 42 manpower, and 35.3 manpower-hours (Table 3). RTLS provided a 96.2% reduction in time taken, 97.6% reduction in manpower, and 97.5% reduction in manpower-hours required. By RTLS, only one staff was required to acquire the activity map and contact list. Conversely, by EMR, two staff from the infection control department were needed to lead the contact tracing efforts, involving 24 additional departments and 40 other staff in the process.

In terms of hospital costs, RTLS required an equipment cost (RTLS platform and staff tags) of $653,594 for the first three years to purchase and maintain the system, whereas EMR method required no additional equipment cost. In terms of manpower costs computed over the simulation exercise, RTLS method incurred a manpower cost of $62 per contact tracing episode, whereas EMR method incurred a manpower cost of $2,125. We computed the expected expenditure over three years to evaluate the long-term cost between RTLS and EMR, as the staff tags had an estimated lifespan of three years. We found that at least 317 contact tracing episodes were needed in the three-year period to obtain cost benefit for RTLS (Table 4).

DISCUSSION

Summary

Overall, RTLS identified almost three times the number of contacts compared to EMR, while achieving that with significantly less time, manpower, manpower-hours, and manpower cost. One caveat to RTLS that may be prohibitive to its implementation is its high cost of entry as the equipment cost incurred can be significant and might take many contact tracing episodes to occur before providing economic benefit.

Interpretation

Similar to the study in Mayo Clinic [5], our study found that RTLS identified more contacts than EMR. Interestingly, RTLS identified an unproportionally large increase of unique contacts in the ED, which was later discovered to be false positive due to off-duty staff keeping their tags in ED lockers. The other RTLS contacts within the ED, the OT, and the ward were found to otherwise be largely accurate. They were identified by RTLS but not EMR for reasons such as doctors and nurses reviewing patients other than the index case, but physically within proximity to the index case. RTLS also detected nurses who chaperoned patients other than the index case to the OT and came in proximity to the index case. Other instances found patients who were physically within the ED as detected by RTLS but omitted by EMR as they were logged as already "discharged" within the EMR system. The value proposition of the RTLS is its capability in detecting such contacts which would otherwise be difficult to establish in the current systems.

The study in Taiwan and Singapore found RTLS to have good sensitivity, specificity and accuracy[6,9]. In our study, RTLS proved to be effective in the identification of contacts as it possibly has better sensitivity than EMR as shown by the identification of contacts that went undetected by EMR, and better specificity by showing some contacts detected by EMR to be false positives due to the subdivision of locations in the RTLS platform. However, non-compliance to tag charging and wearing proved to limit the effectiveness of RTLS. To circumvent such limitations, more staff education and training can be implemented to emphasize the appropriate usage of staff tags. Future tags designs could also be integrated into existing staff cards, which are required for staff to gain access into hospital compound and staff-restricted areas within the campus, thus resolving some of the compliance issues faced in this study.

During the COVID pandemic, Singapore deployed a Bluetooth-based contact tracing app TraceTogether to augment contact tracing capabilities[10]. A validation study comparing the Bluetooth-based app against RTLS by the National Centre for Infectious Disease (NCID) in Singapore found that RTLS has a sensitivity of 95.3% as compared to 6.5% for the Bluetooth-based TraceTogether app[12], suggesting RTLS to be a more effective contact tracing tool in the hospital setting. Despite the better sensitivity, there is still a role for Bluetooth-based contact tracing apps in the community as RTLS would be challenging to implement.

Since the start of COVID-19 till now, much has evolved on the understanding of the disease transmission. It is now known that COVID-19 spread primarily via oral and respiratory aerosols, as compared to large respiratory droplets contaminated with the virus as initially believed[13,14]. Although RTLS does not possess the fidelity to differentiate between low-risk and high-risk clinical activities, we were able to define RTLS contacts based on the duration of exposure (defined at 1min in our study). This can also be redefined based on the transmissibility of the specific disease with each subsequent contact tracing episodes.

Aligned with the study in Mayo Clinic that estimated RTLS to take <5 minutes while EMR to take 30-60 minutes[5], our study found RTLS provided significant time, manpower, and manpower-hour savings. RTLS can consistently deliver similar results regardless of the index case's length of stay, number of locations visited, number of departments involved (e.g. allied health professionals' involvement), or day of contact tracing (weekday vs weekend). Although not specifically measured, contact tracing was swiftly and effectively performed with our RTLS system for 1401 COVID-10 patients in our institution within the first seven months of the COVID-19 pandemic[10]. With EMR, anecdotal evidence revealed that longer lengths of stay, larger numbers of locations visited, larger numbers of departments involved, as well as contact tracing over a weekend can all result in significant delays in contact tracings. Moreover, should all staff in the hospital be tagged, the objective data provided by RTLS would reduce the subsequent work of verification and interview with each contact. Perhaps, the RTLS platform can also be designed to coordinate with other hospital communication systems to trigger automated text messages or emails to be sent to the affected individuals, further reducing the downstream workload of the contact tracing team.

Our cost computations found that initial investment on the RTLS equipment can prove to be costly and present a significant barrier to entry, requiring about two contact tracing episodes per week for RTLS to warrant the investment, while an average of two contact tracing episodes occurred monthly in our hospital (pre-COVID). It is found in other studies that RTLS can be justified in large urban healthcare institutions with diverse patient populations, but not so in small community healthcare institutions[5]. Further studies are required to evaluate and justify the cost of RTLS in Singapore. Alternatively, future studies can look into the cost-benefit analysis of tagging certain groups of the healthcare staff over the others, hence lowering the equipment cost of RTLS.

Privacy concerns can pose significant barrier to adoption and compliance to RTLS tags[12,15]. For privacy reasons, the RTLS data collected is only within the hospital compound and is only stored for a required period (currently set at 3 months). The data obtained retrieved solely for the purposes of contact tracing and is only available to authorised personnel tasked to perform contact tracing work in the hospital.

Limitations

The results of our study are based on one simulation exercise in our institution, hence limiting generalisability. Factors such as index case length of stay, number of locations visited, number of departments involved, or the day contact tracing was performed could all influence the results and necessitate further investigations. Despite the absence of any prior notice, the simulation exercise was held within a month of two prior rehearsals. As such, heightened sense of awareness among hospital staff that an exercise was about to occur, coupled with a possible Hawthorne effect of a simulation exercise, could have resulted in shorter than usual response time. As contacts of the index case were not observed prior to contact tracing, there were no definitive means of determining the true positives and negatives of both methods, though the RTLS was tested and deemed operational prior to the data collection. Hence, we were not able to perform any statistical analysis, nor calculate sensitivity or specificity for our data obtained. Therefore, descriptive statistics were used to describe and compare the contacts derived by RTLS and EMR. Also, only 1000 permanent staff deemed working in high-risk areas were tagged. However, our EMR contacts revealed significant untagged populations such as junior doctors on six-month rotations, allied health professions, and ancillary staff providing meals, cleaning, and porter services. These groups of people were under-represented in this study and their inclusion may result in different contact activities.

Early recognition and mitigation of an EID is paramount in impeding the multiplicative effect of any outbreak, potentially limiting its transmission towards a widespread epidemic. Other studies showed contact tracing to be critical in halting disease transmission[16], and further studies possibly with computational models can more accurately show the clinical benefits conferred by performing contact tracing with RTLS.

Current cost computations consist of only equipment and manpower costs, without considerations on the economic impact of reducing disease transmission. Future studies taking into account the economic impact of reducing disease transmission, particularly in COVID-19, might show RTLS to confer greater economic benefits than presented in this study.

Conclusion

Compared to EMR, we found that RTLS identified contacts in a timelier and more accurate fashion, required fewer manpower and manpower-hours, and has the potential to limit disease transmission. Despite the advantages, high equipment cost is incurred with RTLS and might present significant barrier to adoption. RLTS might be at a nascent stage and not be ready to completely replace conventional methods in contact tracing. However, with subsequent cycles of plan-do-study-act (PDSA)[17] and further studies taking into account the economic impact of reducing disease transmission, RTLS has the potential to be the gold standard in contact tracing methods of the future.

This study explicitly examines the time, manpower, manpower-hours, reduction in disease transmission, and cost of performing contact tracing between RTLS and other conventional means. Our findings hold implications for hospital administrators and healthcare regulators, especially within the country, to relook at how existing standards of contact tracing can be improved.

* This article was written using Standards for QUality Improvement Reporting Excellence (SQUIRE) guidelines[18,19].

DECLARATION

Contributorship Statement

Submitting & Corresponding Author: NG, Guan Yee

- Substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data for the work; AND
- Drafting the work or revising it critically for important intellectual content; AND
- Final approval of the version to be published; AND
- Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Principal Investigator & Co-author: ONG, Biauw Chi

- Substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data for the work; AND
- Drafting the work or revising it critically for important intellectual content; AND
- Final approval of the version to be published; AND
- Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Competing Interests

There are no competing interests for any authors.

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Data Sharing Statement

All data relevant to the study are included in the article.

Ethics Statement

This study involves human participants, but the SingHealth Centralised Institutional Review Board (CIRB) reviewed and exempted this study. CIRB Ref: 2018/3093

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TABLES

Table 1 Comparison of contact list breakdown identified by real-time location system (RTLS) and electronic medical record (EMR). Table created by authors.

Role	RTLS	EMR		
		Tagged	Untagged	Total
Healthcare Workers	157	27	110	137
- Doctors	*8*	*2*	*39*	*41*
- Nurses	*149*	*25*	*19*	*44*
- Allied Health Professionals	*0*	*0*	*11*	*11*
- Ancillary Staff	*0*	*0*	*41*	*41*
Patients	69	55	0	55
Visitors	0	0	96	96
Total	226	82	206	288

Table 2 Comparison of contact list between RTLS and EMR (Tagged) by role only, and by location/role. Table created by authors.

Role	RTLS	EMR (Tagged)	RTLS (but not EMR)	Both RTLS & EMR	EMR (but not RTLS)	Total unique contacts	RTLS increase over EMR (%)
Healthcare Workers	157	27	136	21	6	163	503.7
- Doctors	*8*	*2*	*7*	*1*	*1*	*9*	*350.0*
- Nurses	*149*	*25*	*129*	*20*	*5*	*154*	*516.0*
Patients	69	55	42	27	28	97	76.4
Total	226	82	178	48	34	260	217.1
[a] Detection rate (%)	86.9	31.5				100	175.6
Location / Role	**RTLS**	**EMR (Tagged)**	**RTLS (but not EMR)**	**Both RTLS & EMR**	**EMR (but not RTLS)**	**Total unique contacts**	**RTLS increase over EMR (%)**
Emergency Department	114	47	90	24	23	137	191.5
- Staff (doctors & nurses)	*94*	*10*	*87*	*7*	*3*	*97*	*870.0*
- Patients	*20*	*37*	*3*	*17*	*20*	*40*	*8.1*
Operating Theatre	12	9	6	6	3	15	66.7
- Staff (doctors & nurses)	*5*	*1*	*4*	*1*	*0*	*5*	*400.0*
- Patients	*7*	*8*	*2*	*5*	*3*	*10*	*25.0*
Ward (Inpatient)	101	30	79	22	8	109	263.3
- Staff (doctors & nurses)	*54*	*16*	*41*	*13*	*3*	*57*	*256.3*
- Patients	*47*	*14*	*38*	*9*	*5*	*52*	*271.4*

*[a] Detection rate = [(Contacts detected by either methods)/(Total unique contacts)]*100%*

Table 3 Comparison of time taken, manpower required, and manpower-hours required between RTLS and EMR. Table created by authors.

RTLS

Process	[a] Elapsed time (h)	[b] Manpower required	Manpower-hours required (h)
Index case identified	0	0	0.0
Activity map: Generate activity map via SmartSense	0.1	1	0.1
Activity map: Sort data and fill of MOH activity map template	0.5	1	0.4
Contact list: Generate contact list via SmartSense	0.6	1	0.1
Contact list: Review and sort contact tracing data, and fill MOH contact list template	0.9	1	0.3
	[a] 0.9	[b] 1	0.9
Downstream Departments		**Manpower required**	**Manpower-hours required (h)**
None		0	0.0

EMR

Process	[a] Elapsed time (h)	[b] Manpower required	Manpower-hours required (h)
Index case identified	0	0	0.0
Activity map: SAP check (hospital registration system)	0.1	1	0.1
Activity map: Contact OT (OT journey)	0.5	1	0.4
Activity map: SCM check (EMR)	0.6	1	0.6
Activity map: Contact ED (ED journey)	0.8	1	0.3
Activity map: Verify data and fill of MOH activity map template	1.5	2	0.8
Contact list: Contact MI (list of exposed patients)	1.7	1	0.2
Contact list: Email all stakeholders - ED, OT, Ward, AHP (13dept), Anc staff (5dept)	1.9	1	1.1
Contact list: Contact AVMS (list of exposed visitors)	2.2	2	0.4
Contact list: Sort MI data (list of exposed patients)	3.9	1	0.2
Contact list: Contact IHIS (author list of EMR)	4	1	0.2
Contact list: Sort IHIS data (author list of EMR)	7.2	1	0.5
Contact list: Compile data, call and clarify non-response / missing data, and fill MOH contact list template	23.7	2	12.0
	[a] 23.7	[b] 2	16.4
Downstream Departments		**Manpower required**	**Manpower-hours required (h)**
Emergency Department		1	1.3
Operating Theatre		1	1.0
Ward 19		1	1.0
Management Information - eHints		1	0.5
AVMS dept		4	2.5
Integrated Health Information Systems		2	1.5
Audiology		1	0.2
Clinical Measurement Centre		1	0.1
Dietetics		1	0.1
Medical Social Services		1	0.2

				Occupational Therapy		1	0.3
				Pathology		1	0.1
				Pharmacy		2	0.7
				Physiotherapy		3	1.2
				Podiatry		2	0.5
				Psychology		1	0.3
				Radiology		1	0.5
				Respiratory Therapy		1	0.8
				Speech Therapy		1	0.2
				Environmental Services		6	1.8
				Facilities Management & Engineering		1	2.0
				General Services		2	1.2
				Materials Management		1	0.8
				Security		3	0.3
		0	0.0			40	18.9
	[a] Elapsed time (h)	**[b] Manpower required**	**Manpower-hours required (h)**		**[a] Elapsed time (h)**	**[b] Manpower required**	**Manpower-hours required (h)**
Total	**[a] 0.9**	**[b] 1**	**0.9**	**Total**	**[a] 23.7**	**[b] 42**	**35.3**
Decrease over EMR (%)	**96.2**	**97.6**	**97.5**				

[a] Elapsed time refers to the amount of time that has passed since the start of the exercise at the point of completion of a process, hence the total elapsed time is not a simple sum of the above cells.
[b] Manpower required is the number of staff it took to perform the process. Many of the processes were performed by the same staff, and hence the total manpower required is not a simple sum of the above cells.

Table 4 Comparison of cost between RTLS and EMR. Table created by authors.

Cost	**RTLS**	**EMR**
[a] Equipment cost (for first three years)	$653,594	$0
[b] Manpower cost (for each contact tracing episode)	$62	$2,125
Case scenarios		
36 contact tracing episodes in 3 years	$655,826	$76,500
156 contact tracing episodes in 3 years	$663,266	$331,500
317 contact tracing episodes in 3 years	$673,248	$673,625

[a] Equipment cost (RTLS) = cost of RTLS platform + cost of staff tags
*[b] Manpower cost = (manpower-hours of Staff 1 * norm cost of Staff 1) + (manpower-hours of Staff 2 * norm cost of Staff 2) + … + (manpower-hours of Staff N * norm cost of Staff N)*

FIGURES

Figure 1 Comparison of RTLS vs EMR (tagged) broken down into: (a) total - staff & patients, (b) total - staff (doctors & nurses), (c) total - patients, (d) ED - staff (doctors & nurses), (e) ED - patients, (f) OT - staff (doctors & nurses), (g) OT - patients, (h) Ward - staff (doctors & nurses), and (i) Ward - patients. Figure created by authors.

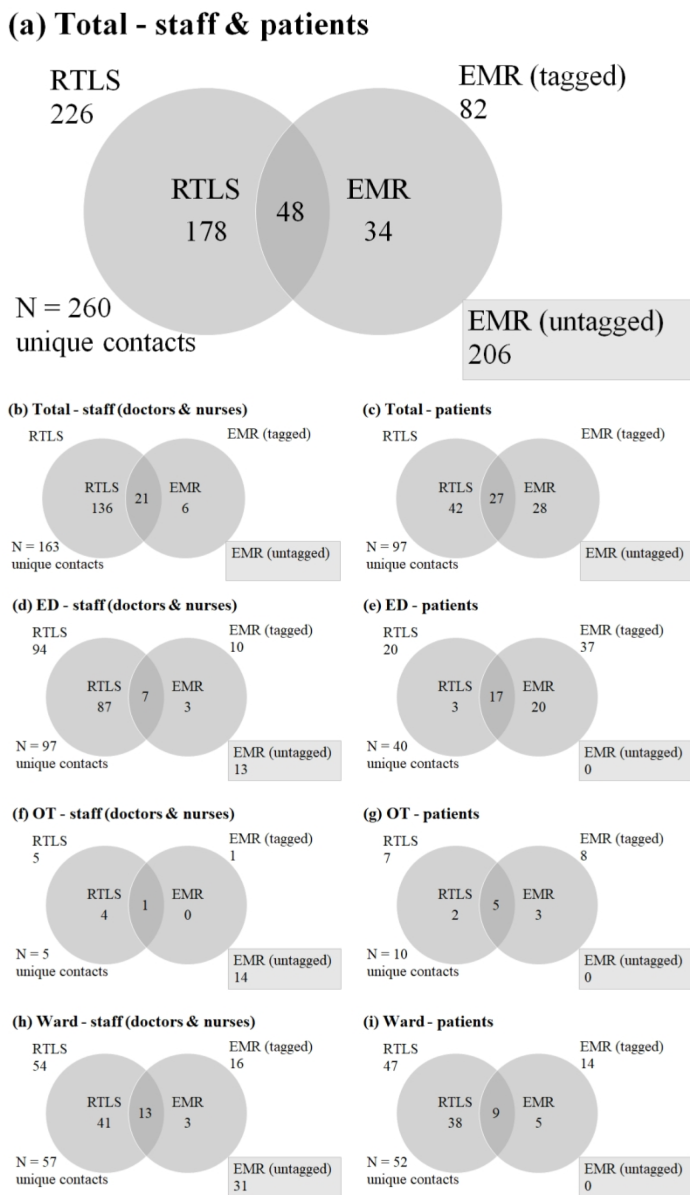

Figure 1 Comparison of RTLS vs EMR (tagged) broken down into: (a) total - staff & patients, (b) total - staff (doctors & nurses), (c) total - patients, (d) ED - staff (doctors & nurses), (e) ED - patients, (f) OT - staff (doctors & nurses), (g) OT - patients, (h) Ward - staff (doctors & nurses), and (i) Ward - patients. Figure created by authors.

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Revised Standards for Quality Improvement Reporting Excellence (SQUIRE 2.0) September 15, 2015

Text Section and Item Name	Section or Item Description	
Notes to authors	• The SQUIRE guidelines provide a framework for reporting new knowledge about how to improve healthcare • The SQUIRE guidelines are intended for reports that describe system level work to improve the quality, safety, and value of healthcare, and used methods to establish that observed outcomes were due to the intervention(s). • A range of approaches exists for improving healthcare. SQUIRE may be adapted for reporting any of these. • Authors should consider every SQUIRE item, but it may be inappropriate or unnecessary to include every SQUIRE element in a particular manuscript. • The SQUIRE Glossary contains definitions of many of the key words in SQUIRE. • The Explanation and Elaboration document provides specific examples of well-written SQUIRE items, and an in-depth explanation of each item. • Please cite SQUIRE when it is used to write a manuscript.	
Title and Abstract		Page
1. Title	Indicate that the manuscript concerns an initiative to improve healthcare (broadly defined to include the quality, safety, effectiveness, patient-centeredness, timeliness, cost, efficiency, and equity of healthcare)	1
2. Abstract	a. Provide adequate information to aid in searching and indexing b. Summarize all key information from various sections of the text using the abstract format of the intended publication or a structured summary such as: background, local problem, methods, interventions, results, conclusions	3 - 4
Introduction	*Why did you start?*	
3. Problem Description	Nature and significance of the local problem	5
4. Available knowledge	Summary of what is currently known about the problem, including relevant previous studies	6 - 7

5. Rationale	Informal or formal frameworks, models, concepts, and/or theories used to explain the problem, any reasons or assumptions that were used to develop the intervention(s), and reasons why the intervention(s) was expected to work	7
6. Specific aims	Purpose of the project and of this report	7
Methods	*What did you do?*	
7. Context	Contextual elements considered important at the outset of introducing the intervention(s)	8
8. Intervention(s)	a. Description of the intervention(s) in sufficient detail that others could reproduce it b. Specifics of the team involved in the work	9 - 10
9. Study of the Intervention(s)	a. Approach chosen for assessing the impact of the intervention(s) b. Approach used to establish whether the observed outcomes were due to the intervention(s)	9 - 10
10. Measures	a. Measures chosen for studying processes and outcomes of the intervention(s), including rationale for choosing them, their operational definitions, and their validity and reliability b. Description of the approach to the ongoing assessment of contextual elements that contributed to the success, failure, efficiency, and cost c. Methods employed for assessing completeness and accuracy of data	9
11. Analysis	a. Qualitative and quantitative methods used to draw inferences from the data b. Methods for understanding variation within the data, including the effects of time as a variable	10
12. Ethical Considerations	Ethical aspects of implementing and studying the intervention(s) and how they were addressed, including, but not limited to, formal ethics review and potential conflict(s) of interest	10
Results	*What did you find?*	
13. Results	a. Initial steps of the intervention(s) and their evolution over time (*e.g.*, time-line diagram, flow chart, or table), including modifications made to the intervention during the project b. Details of the process measures and outcome c. Contextual elements that interacted with the intervention(s) d. Observed associations between outcomes, interventions, and relevant contextual elements e. Unintended consequences such as unexpected benefits, problems, failures, or costs associated with the intervention(s). f. Details about missing data	11 -12
Discussion	*What does it mean?*	
14. Summary	a. Key findings, including relevance to the rationale and specific aims b. Particular strengths of the project	13

15. Interpretation	a. Nature of the association between the intervention(s) and the outcomes b. Comparison of results with findings from other publications c. Impact of the project on people and systems d. Reasons for any differences between observed and anticipated outcomes, including the influence of context e. Costs and strategic trade-offs, including opportunity costs	13 - 15
16. Limitations	a. Limits to the generalizability of the work b. Factors that might have limited internal validity such as confounding, bias, or imprecision in the design, methods, measurement, or analysis c. Efforts made to minimize and adjust for limitations	15 - 16
17. Conclusions	a. Usefulness of the work b. Sustainability c. Potential for spread to other contexts d. Implications for practice and for further study in the field e. Suggested next steps	16 - 17
Other information		
18. Funding	Sources of funding that supported this work. Role, if any, of the funding organization in the design, implementation, interpretation, and reporting	17

Table 2. Glossary of key terms used in SQUIRE 2.0. This Glossary provides the intended meaning of selected words and phrases as they are used in the SQUIRE 2.0 Guidelines. They may, and often do, have different meanings in other disciplines, situations, and settings.

Assumptions
Reasons for choosing the activities and tools used to bring about changes in healthcare services at the system level.

Context
Physical and sociocultural makeup of the local environment (for example, external environmental factors, organizational dynamics, collaboration, resources, leadership, and the like), and the interpretation of these factors ("sense-making") by the healthcare delivery professionals, patients, and caregivers that can affect the effectiveness and generalizability of intervention(s).

Ethical aspects
The value of system-level initiatives relative to their potential for harm, burden, and cost to the stakeholders. Potential harms particularly associated with efforts to improve the quality, safety, and value of healthcare services include opportunity costs, invasion of privacy, and staff distress resulting from disclosure of poor performance.

Generalizability
The likelihood that the intervention(s) in a particular report would produce similar results in other settings, situations, or environments (also referred to as external validity).

Healthcare improvement
Any systematic effort intended to raise the quality, safety, and value of healthcare services, usually done at the system level. We encourage the use of this phrase rather than "quality improvement," which often refers to more narrowly defined approaches.

Inferences
The meaning of findings or data, as interpreted by the stakeholders in healthcare services – improvers, healthcare delivery professionals, and/or patients and families

Initiative
A broad term that can refer to organization-wide programs, narrowly focused projects, or the details of specific interventions (for example, planning, execution, and assessment)

Internal validity
Demonstrable, credible evidence for efficacy (meaningful impact or change) resulting from introduction of a specific intervention into a particular healthcare system.

Intervention(s)
The specific activities and tools introduced into a healthcare system with the aim of changing its performance for the better. Complete description of an intervention includes its inputs, internal activities, and outputs (in the form of a logic model, for example), and the mechanism(s) by which these components are expected to produce changes in a system's performance.

Opportunity costs

Loss of the ability to perform other tasks or meet other responsibilities resulting from the diversion of resources needed to introduce, test, or sustain a particular improvement initiative

Problem
Meaningful disruption, failure, inadequacy, distress, confusion or other dysfunction in a healthcare service delivery system that adversely affects patients, staff, or the system as a whole, or that prevents care from reaching its full potential

Process
The routines and other activities through which healthcare services are delivered

Rationale
Explanation of why particular intervention(s) were chosen and why it was expected to work, be sustainable, and be replicable elsewhere.

Systems
The interrelated structures, people, processes, and activities that together create healthcare services for and with individual patients and populations. For example, systems exist from the personal self-care system of a patient, to the individual provider-patient dyad system, to the microsystem, to the macrosystem, and all the way to the market/social/insurance system. These levels are nested within each other.

Theory or theories
Any "reason-giving" account that asserts causal relationships between variables (causal theory) or that makes sense of an otherwise obscure process or situation (explanatory theory). Theories come in many forms, and serve different purposes in the phases of improvement work. It is important to be explicit and well-founded about any informal and formal theory (or theories) that are used.