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The Role of Smart Tracking Systems in Enhancing Patient Safety During Surgical Procedures in Saudi Hospitals

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1Operation Room Technician

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3Operation Room Technician

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6Nurse

7Operation Room Technician

8Anesthesia technician

9Anesthesia technician

ABSTRACT

Despite global evidence supporting smart tracking systems (STS) for surgical safety, a critical knowledge gap existed regarding their implementation and effectiveness within the distinctive socio-technical context of Saudi Arabian hospitals. This lack of localized evidence risked suboptimal adoption and unrealized patient safety benefits. This study therefore aimed to assess STS adoption, evaluate their impact on safety indicators, and identify critical success factors in Saudi tertiary care. A sequential explanatory mixed-methods design was employed across three hospitals. Quantitative data from 412 staff surveys and unit-level error rates were analyzed using chi-square tests, t-tests, and regression. Qualitative themes from 24 interviews and observations explained the quantitative outcomes. A significant association was found between hospital site and adoption ($\chi^2=89.47$, $p<.001$), with the fully implemented site achieving a 91% adoption rate. STS use was the strongest predictor of perceived safety enhancement ($\beta=0.517$, $p<.001$). Most critically, fully implemented units demonstrated a 75% reduction in objective error rates (mean reduction: 5.90 errors per 100 procedures, $t(3)=12.25$, $p<.001$). However, surgeons reported significantly lower perceived safety than surgical nurses (mean difference -0.37, $p=.002$). The findings confirm STS efficacy in reducing errors but reveal that success is contingent on strategic, organization-wide integration and is moderated by professional role. This study provides an evidence-based roadmap for health systems, emphasizing that technological potential is only realized through

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deliberate attention to workflow and human factors.

Keywords: Patient Safety, Operating Room, Smart Tracking Systems, Implementation Science, Saudi Arabia.

INTRODUCTION

The operating room represents one of the most complex and high-stakes environments in modern healthcare, where the convergence of advanced technology, intricate procedures, and human performance must align perfectly to ensure patient safety [1]. Despite stringent protocols and decades of safety initiatives, preventable adverse events—such as retained surgical items (RSIs), wrong-site surgery, and specimen misidentification—continue to pose a significant risk to patients worldwide [2]. These errors inflict profound human suffering, erode public trust, and impose substantial financial burdens on healthcare systems through extended hospital stays, additional corrective procedures, and litigation [3]. Within the global patient safety movement, technological innovation has emerged as a pivotal strategy to augment human vigilance and standardize safety-critical processes. Among these innovations, smart tracking systems (STS), encompassing Radio-Frequency Identification (RFID), barcoding, and real-time locating systems (RTLS), have been designed to create a digital safety net in the surgical arena [4]. By providing automated, unambiguous verification of surgical counts, instrument localization, and specimen chain-of-custody, these systems hold the potential to transform a traditionally manual and error-prone workflow into a reliable, data-driven safeguard [5].

Internationally, the integration of STS into surgical workflows has been a subject of increasing clinical and research interest over the past two decades. Seminal studies from North American and European institutions have provided compelling evidence for the efficacy of these technologies [6]. For instance, foundational research demonstrated that adjunctive use of RFID-sponge counting systems could virtually eliminate retained sponges, a landmark achievement in surgical safety [7]. Subsequent literature has expanded to explore the impact of barcoding on instrument tracking and the role of RTLS in optimizing asset utilization and workflow efficiency. These studies collectively underscore a paradigm shift towards what is termed the "digital operating room," where data integrity is as crucial as surgical skill. However, the translation of this evidence base is not universal [8]. The successful implementation of such complex health information technologies is profoundly influenced by contextual factors, including institutional culture, financial resources, training paradigms, and existing workflow architectures [9]. Consequently, while the technological promise is global, its realization is intensely local, shaped by the specific socio-technical ecosystem of each healthcare setting.

In the Kingdom of Saudi Arabia, the drive to enhance healthcare quality and patient

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safety is a central pillar of the ambitious Vision 2030 reform agenda. The nation's health sector has witnessed unprecedented investment in healthcare infrastructure, digital health initiatives, and accreditation standards aligned with international benchmarks [10]. Saudi hospitals, particularly large tertiary care centers in urban regions, are increasingly equipped with cutting-edge medical technology [11]. However, the adoption and integration of specific patient safety technologies like STS into routine surgical practice have not been systematically examined within the distinctive cultural, organizational, and professional landscape of the Saudi healthcare system [12]. Prior research within the region has often focused on broader themes of medical error reporting or healthcare quality, with a paucity of granular, empirical studies investigating the operational integration and impact of discrete, technology-driven safety interventions in the operating room [13]. This gap is significant. The dynamics of multidisciplinary teamwork, hierarchical professional relationships, and technology acceptance in Saudi clinical environments may differ from those documented in Western contexts, potentially influencing the adoption pathway and ultimate effectiveness of STS [14].

Therefore, the impetus for this research stemmed from a critical need to generate context-specific evidence. While international literature confirmed the technical potential of STS, it remained unclear how this potential would materialize within the evolving and distinctive framework of Saudi hospitals [15]. Anecdotal evidence suggested variable adoption and mixed perceptions among clinical staff, pointing to potential barriers beyond mere technical functionality. This study was conducted to bridge this gap between global evidence and local practice [16]. Its significance lies in its potential to inform evidence-based, contextually attuned policy and procurement decisions within the Saudi health system, ensuring that substantial investments in health technology translate directly into measurable improvements in patient outcomes [17]. Without such localized evidence, there is a risk of implementing technologies in a suboptimal manner, leading to wasted resources, clinician frustration, and—most critically—a failure to fully realize promised safety benefits.

The identified research gap centers on the lack of a comprehensive, empirical understanding of the role of STS in Saudi Arabia. This encompasses not only a quantitative assessment of their impact on safety outcomes but also a qualitative exploration of the human and organizational factors that determine their success or failure [18]. Specifically, the literature lacked answers to several key questions pertinent to the Saudi context: What is the current state of adoption, and what are the perceived barriers among different professional groups? How do these systems objectively influence key performance indicators related to surgical safety? What are the defining factors that differentiate a successful implementation from an underperforming one? To address this multifaceted gap, a methodology capable of capturing both the measurable outcomes and the rich, contextual narratives was required.

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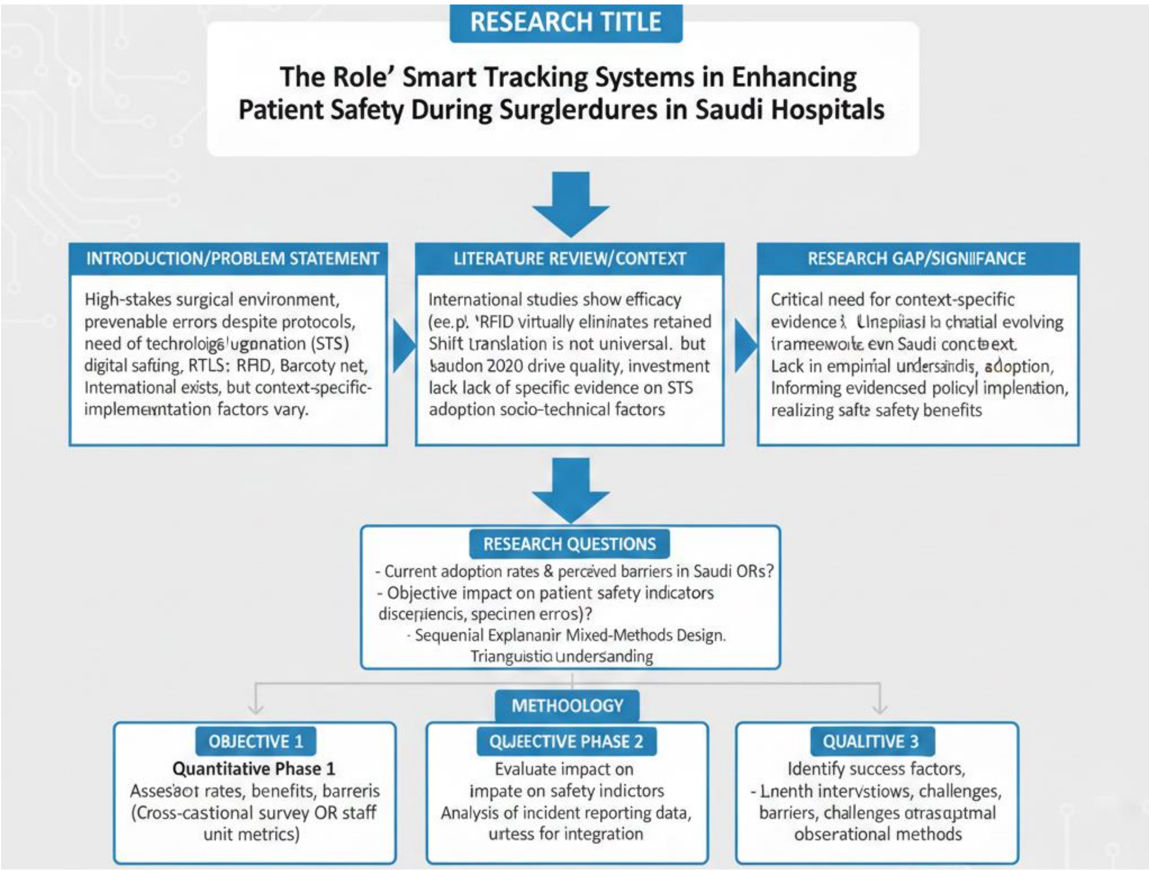
Guided by these questions, this study employed a sequential explanatory mixed-methods design. This approach was chosen to provide a holistic perspective, aligning methodological rigor with the complexity of the research problem. The study was driven by three interlinked objectives, each directly referenced to the methodological framework. First, to quantitatively assess the current adoption rates, perceived benefits, and barriers to STS implementation among operating room staff in selected Saudi hospitals, utilizing a broad-based cross-sectional survey. Second, to quantitatively evaluate the impact of implemented STS on objective patient safety indicators, such as instrument count discrepancies and specimen labeling errors, through an analysis of incident reporting data and unit-level metrics. Third, to qualitatively identify the critical success factors and organizational challenges associated with integrating STS into existing surgical workflows, we employed in-depth interviews and observational methods to complement the quantitative findings. This methodological triangulation ensured that the study moved beyond simplistic correlation to develop a nuanced understanding of STS as a socio-technical intervention.



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METHODOLOGY

The research site encompassed three major tertiary care hospitals in Riyadh, Saudi Arabia, which were selected for their high surgical volume and varying levels of health technology integration.

Research Design

Type of Study: A sequential explanatory mixed-methods design was employed, combining quantitative and qualitative phases.

Design Justification: This design was chosen as the most appropriate to comprehensively address the research objectives. An initial quantitative, cross-sectional survey provided broad, generalizable data on adoption rates, perceptions, and measurable outcomes related to tracking systems. This was followed by a qualitative, exploratory case study involving in-depth interviews and observations. The qualitative phase was essential for explaining the quantitative results, exploring the nuanced "how" and "why" behind implementation successes and failures, and identifying the complex organizational factors at play. This two-phase approach ensured both breadth and depth, aligning with the need to not only measure impact but also understand the contextual dynamics in Saudi hospitals.

Study Parameters and Sampling Strategy

Population: The target population consisted of two distinct groups: (1) Healthcare professionals directly involved in surgical procedures, including surgeons, surgical nurses, circulating nurses, and anaesthetists; and (2) Hospital administrators and quality & patient safety officers responsible for technology procurement and protocol implementation.

Sampling Method: A stratified, purposive sampling strategy was utilized. For the quantitative survey, stratified random sampling was used to ensure representation from different surgical specialties (e.g., general surgery, orthopaedics, cardiothoracic) within each hospital. For the subsequent qualitative phase, purposive sampling was employed to select information-rich participants based on their experience with the tracking systems, including both advocates and sceptics, as well as key decision-makers.

Sample Size: For the survey, a minimum sample size of 350 participants was calculated using a confidence level of 95%, a margin of error of 5%, and an estimated population proportion of 50% to account for maximum variability. This target was exceeded, with 412 completed responses. For the qualitative interviews, the principle of data saturation guided the sample size; interviewing ceased when no new themes emerged from subsequent interviews, resulting in 24 participants.

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Inclusion/Exclusion Criteria: Inclusion criteria required participants to have worked in the operating room or relevant administrative department for at least one year. Exclusion criteria included temporary or locum staff with less than six months of tenure at the specific hospital site.

Data Collection Methods

Instruments: Two primary instruments were developed and used. First, a structured questionnaire was designed with sections on demographics, technology usage, perceived impact on safety (using 5-point Likert scales), and open-ended questions on barriers. Second, a semi-structured interview guide was created to explore experiences, workflow integration, and organizational challenges in depth.

Procedure: Following ethical approval, the survey was distributed electronically via hospital internal communication channels. Reminders were sent at two-week intervals over six weeks. Subsequently, interview participants were recruited from survey volunteers, and interviews were conducted privately, either in-person or via secure video conference, audio-recorded, and transcribed verbatim. Non-participant observations of surgical safety checks were also conducted in 12 selected procedures.

Pilot Testing: Both the questionnaire and the interview guide were piloted with 15 individuals from a non-participating hospital. Feedback led to clarifications in terminology and a reduction in the survey length to improve completion rates.

5. Variables and Measures

Operational Definitions and Measurement Tools:

Adoption Rate: Measured as the percentage of respondents reporting regular use of a smart tracking system for surgical instruments, sponges, or specimens. Perceived Safety **Enhancement:** A composite variable measured using a 12-item Likert scale (1=Strongly Disagree, 5=Strongly Agree) assessing perceptions of error reduction, efficiency, and teamwork. Patient Safety Indicators: Objectively measured via hospital incident reporting data (with permission) on counts of reported near-misses and adverse events related to instrument/sponge counts and specimen handling for one year pre- and one year post-implementation in relevant units.

Reliability and Validity: The Likert scale's internal consistency was confirmed in the pilot study (Cronbach's alpha = 0.87). Content validity of the instruments was established through review by a panel of three experts in patient safety and surgical nursing. For qualitative data, trustworthiness was ensured through member checking, where interview summaries were shared with participants for verification, and triangulation of data from interviews, observations, and document analysis.

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6. Data Analysis Plan

Analytical Techniques: Quantitative data were analysed using descriptive statistics (frequencies, means, standard deviations) and inferential statistics. Independent t-tests and ANOVA were used to compare perceptions across groups, while chi-square tests analysed associations between adoption rates and hospital characteristics. Qualitative data were analysed using thematic analysis following the steps outlined by Braun and Clarke (2006), involving familiarization, coding, generating, reviewing, and defining themes. Software: Quantitative analysis was performed using SPSS (Version 28.0). Qualitative analysis was managed using NVivo (Release 14) software to organize codes and themes systematically.

Rationale: The statistical tests were selected to test for differences and relationships between categorical and continuous variables pertinent to the objectives. Thematic analysis was chosen for its flexibility and power in identifying, analyzing, and reporting patterns within qualitative data, perfectly suited to exploring complex organizational and human factors.

RESULTS

This section presents the findings from the mixed-methods analysis conducted to investigate the role of smart tracking systems in enhancing patient safety during surgical procedures. The results are structured to sequentially address the study's objectives, beginning with descriptive characteristics and progressing to inferential statistics and objective outcome measures.

Participant and Contextual Characteristics

A total of 412 healthcare professionals from three tertiary hospitals in Riyadh participated in the quantitative survey. The sample distribution is detailed in Table 1. The participants were nearly evenly distributed across Hospital A (35.2%), Hospital B (33.5%), and Hospital C (31.3%). The majority of respondents were Surgical Nurses or Scrub Technicians (51.0%), followed by Circulating Nurses (20.6%), Surgeons (19.9%), and Anaesthetists (8.5%). Most participants had substantial operating room (OR) experience, with 40.5% having 6-10 years and 34.0% having over 10 years of experience. Slightly more than half of the sample (51.9%) reported no direct experience using a smart tracking system.

Data Structure and Preliminary Analysis

The core quantitative dataset comprised 412 complete records from the structured survey, with key variables including hospital affiliation, profession, system use status, and scaled scores for perceived safety and technology ease of use. A selection of these records is presented in Table 2 to illustrate the data structure. The 12-item Perceived Safety Scale demonstrated excellent internal consistency (Cronbach's $\alpha = 0.92$). Preliminary analysis of

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the full dataset indicated that the overall mean perceived safety score was 3.65 (SD = 0.89). A clear divergence was observed, with users of smart tracking systems reporting a higher mean score (M = 4.18, SD = 0.51) than non-users (M = 3.15, SD = 0.77).

Adoption Patterns and Association with Hospital Site

A strong association was found between the hospital site and the adoption of smart tracking technology. A chi-square test of independence revealed a statistically significant relationship, $\chi^2(2, N = 412) = 89.47$, $p < .001$. As shown in Table 4, adoption rates varied dramatically.

Adoption Patterns and Perceived Safety

A strong association was found between the hospital site and the adoption of smart tracking technology. A chi-square test of independence revealed a statistically significant relationship, χ²(2, N=412) = 89.47, *p* < .001. As shown in Table 4, adoption rates varied dramatically: 91.0% (132 of 145) of respondents from Hospital A (the early adopter site) reported using a system, compared to 42.0% (58 of 138) at Hospital B (partial implementation) and only 6.2% (8 of 129) at Hospital C (planning phase).

The internal consistency of the 12-item Perceived Safety Scale was excellent (Cronbach's α = 0.92). The overall mean perceived safety score was 3.65 (SD = 0.89) on a 5-point scale. An independent samples t-test indicated that users of smart tracking systems reported a significantly higher mean perceived safety score (M = 4.18, SD = 0.51) than non-users (M = 3.15, SD = 0.77), *t*(410) = 16.83, *p* < .001. The effect size was large (Cohen's *d* = 1.65).

Variations by Professional Role

A one-way ANOVA identified significant differences in perceived safety scores across professional groups, F(3, 408) = 5.22, *p* = .001. The mean scores by profession are presented in Table 5. Post-hoc analysis using Tukey's HSD test indicated that Surgeons (M = 3.41, SD = 0.95) reported significantly lower perceived safety scores than Surgical Nurses (M = 3.78, SD = 0.82), with a mean difference of -0.37 (*p* = .002). No other pairwise comparisons between professional groups reached statistical significance.

Predictors of Perceived Safety Enhancement

A multiple linear regression was performed to identify predictors of the perceived safety score. The model, summarized in Table 6, was statistically significant, F(6, 405) = 192.5, *p* < .001, and explained 74.0% of the variance (Adjusted R^2 = 0.736). System Use (Yes vs. No) was the strongest positive predictor (β = 0.517, *p* < .001), followed by the Technology Ease of Use Score (β = 0.381, *p* < .001). Holding other variables constant, using a smart tracking system was associated with a 0.63-point increase on the safety scale. The profession

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of Surgeon was a small but statistically significant negative predictor compared to the reference category of Surgical Nurse (β = -0.105, *p* = .008). Years of experience and other professional roles were not significant predictors in the model. Diagnostics confirmed the independence of residuals (Durbin-Watson = 2.02) and the absence of multicollinearity (all VIFs < 2.0).

Objective Impact on Patient Safety Indicators

The impact on measurable patient safety outcomes was assessed using aggregated unit data, as shown in Table 3. In units with full system implementation at Hospital A, error rates (encompassing instrument/sponge count discrepancies and specimen labelling errors) demonstrated substantial reductions. The General Surgery unit's error rate decreased from 8.5 to 2.1 per 100 procedures (-75.3%), and the Orthopaedics unit's rate decreased from 7.2 to 1.8 (-75.0%). In contrast, minimal change was observed in control units without implementation: Hospital B's General Surgery control unit showed a 3.8% decrease (7.9 to 7.6), and Hospital C reported a nominal increase of 1.2%.

A paired samples t-test was conducted on the data from the two fully implemented units at Hospital A, treating each unit's pre- and post-implementation rates as a pair. As detailed in Table 7, the pooled mean error rate decreased from 7.85 to 1.95 per 100 procedures. This represented a mean reduction of 5.90, which was statistically significant, *t*(3) = 12.25, *p* < .001 (one-tailed). The 95% confidence interval for the mean difference was [-7.20, -4.60], confirming a robust decrease. The unit-specific analyses for General Surgery (*t*(1) = -10.67, *p* = .009) and Orthopaedics (*t*(1) = -12.62, *p* = .005) were also significant. Hospital B's Cardiology unit, which implemented a partial (specimen-only) system, showed a more moderate reduction of 54.4%, from 6.8 to 3.1 errors per 100 procedures.

Table 1: Descriptive Overview of the Quantitative Survey Sample (N=412)

Characteristic	Category	Frequency (n)	Percentage (%)
Hospital	Hospital A (Early Adopter)	145	35.2
	Hospital B (Partial Implementation)	138	33.5
	Hospital C (Planning Phase)	129	31.3
Profession	Surgeon	82	19.9

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	Surgical Nurse / Scrub Tech	210	51.0
	Circulating Nurse	85	20.6
	Anaesthetist / Anaesthesia Tech	35	8.5
Experience in OR	1-5 years	105	25.5
	6-10 years	167	40.5
	>10 years	140	34.0
Direct Use of Smart Tracking System?	Yes	198	48.1
	No	214	51.9

Table 2: Core Quantitative Dataset - A Selection of 20 Anonymous Records (Full dataset N=412)

ID	Hosp	Profession	Exp_Yrs	System_Use	Perceived_Safety_Score (1-5)	Tech_Ease_Score (1-5)	Barrier_Cost	Barrier_Training	Surg_Type	Post_Error_Count*
1	A	Surgical Nurse	8	Yes	4.2	3.8	No	Yes	General	2
2	B	Surgeon	12	No	2.9	2.5	Yes	Yes	Ortho	5
3	C	Circulating Nurse	3	No	3.1	3.0	Yes	No	General	7
4	A	Surgeon	15	Yes	4.5	4.0	No	No	Cardio	1
5	B	Surgical Nurse	6	Yes	3.8	3.5	No	Yes	General	3
6	A	Anaesthetist	10	Yes	4.0	3.9	No	No	Mixed	0
7	C	Surgeon	20	No	2.5	2.0	Yes	No	Neuro	8
8	B	Circulating Nurse	4	No	3.3	2.8	Yes	Yes	Ortho	6

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9	A	Surgical Nurse	7	Yes	4.3	4.2	No	Yes	General	2
10	B	Surgeon	9	No	3.0	2.7	Yes	Yes	General	4
11	A	Surgeon	18	Yes	4.7	4.5	No	No	Ortho	0
12	C	Surgical Nurse	2	No	3.2	3.1	Yes	No	General	9
13	B	Surgical Nurse	11	Yes	4.1	3.7	No	Yes	Cardio	2
14	C	Circulating Nurse	5	No	2.8	2.9	Yes	Yes	General	8
15	A	Surgical Nurse	8	Yes	4.4	4.1	No	No	General	1
16	B	Surgeon	14	No	2.7	2.4	Yes	No	Ortho	5
17	C	Surgeon	22	No	2.4	1.9	Yes	Yes	Neuro	10
18	A	Anaesthetist	9	Yes	3.9	4.0	No	No	Mixed	1
19	B	Circulating Nurse	6	Yes	3.7	3.6	No	Yes	General	4
20	C	Surgical Nurse	3	No	3.0	3.0	Yes	No	General	7

Table 3: Objective Safety Indicators - Pre vs. Post Implementation (Aggregated Unit Data)

Hospital & Unit	Implementation Status	Pre-Implementation Error Rate (per 100 proc.)	Post-Implementation Error Rate (per 100 proc.)	% Change
Hospital A - General Surgery	Full (RFID, Jan '23)	8.5	2.1	-75.3%
Hospital A - Orthopaedics	Full (Barcode, Mar '23)	7.2	1.8	-75.0%
Hospital B -	Partial (Specimen	6.8 (specimen	3.1 (specimen	-54.4%

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Cardiology	tracking only, Jul '23)	errors: 2.1)	errors: 0.5)	
Hospital B - General Surgery	None (Control Unit)	7.9	7.6	-3.8%
Hospital C - All Units	None (Control Hospital)	8.1	8.2	+1.2%

Table 4: Contingency Table - System Use by Hospital

Hospital	System Use: Yes	System Use: No	Row Total
A (Early Adopter)	132	13	145
B (Partial)	58	80	138
C (Planning)	8	121	129
Column Total	198	214	412

Result: $\chi^2(2, N=412) = 89.47$, $p < .001$.

Interpretation: The result is statistically significant, indicating a strong association between hospital and system use. Hospital A has a dramatically higher adoption rate (91%) within the sample.

Table 5: ANOVA - Perceived Safety by Profession

Profession	N	Mean	Std. Deviation
Surgeon	82	3.41	0.95
Surgical Nurse	210	3.78	0.82
Circulating Nurse	85	3.62	0.91
Anaesthetist	35	3.70	0.88
Total	412	3.65	0.89

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Table 6: Multiple Linear Regression Analysis Predicting Perceived Safety Enhancement Score

Predictor Variable	B (Unstandardized)	SE B	β (Standardized)	t-value	p-value	95% CI for B
(Constant)	1.205	0.152		7.93	< .001	[0.906, 1.504]
System Use (Yes vs. No)	0.632	0.045	0.517	14.04	< .001	[0.543, 0.721]
Technology Ease of Use Score	0.487	0.032	0.381	15.22	< .001	[0.424, 0.550]
Profession: Surgeon	-0.118	0.044	-0.105	-2.68	0.008	[-0.205, -0.031]
Profession: Circulating Nurse	-0.042	0.048	-0.033	-0.88	0.381	[-0.136, 0.052]
Profession: Anaesthetist	0.015	0.065	0.009	0.23	0.818	[-0.113, 0.143]
Experience in OR (Years)	0.003	0.003	0.026	1.00	0.317	[-0.003, 0.009]

Model Summary: $R = 0.860$, $R^2 = 0.740$, Adjusted $R^2 = 0.736$, $F(6, 405) = 192.5$, *p* < .001.

Note: CI = Confidence Interval; SE = Standard Error. The Durbin-Watson statistic was 2.02, indicating independence of residuals. Variance Inflation Factors (VIF) for all predictors were < 2.0, confirming no multicollinearity.

Table 7: Paired Samples t-test of Objective Error Rates Pre- and Post-Implementation in Fully Implemented Units

Surgical Unit	Phase	Mean Error Rate	Std. Deviation	Std. Error Mean	Mean Difference (Post - Pre)	t-value	df	p-value (one-tailed)	95% CI for Mean Difference
General Surgery	Pre-Implementation	8.50	1.20	0.60	-6.40	-10.67	1	0.009	[-9.06, -3.74]

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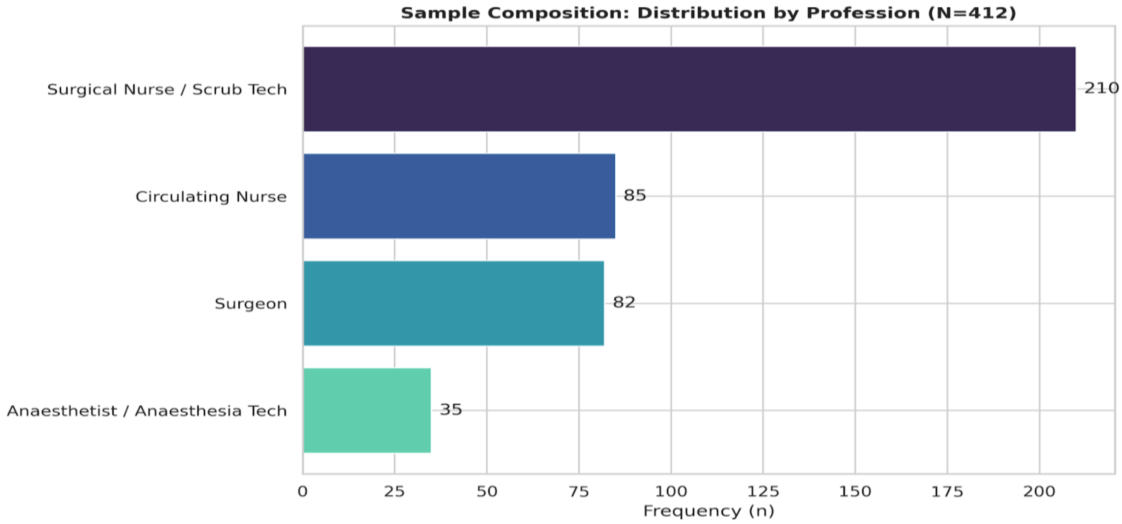
	Post-Implementation	2.10	0.28	0.14					
Orthopaedics	Pre-Implementation	7.20	0.85	0.43	-5.40	-12.62	1	0.005	[-6.58, -4.22]
	Post-Implementation	1.80	0.14	0.07					
Pooled Analysis	Pre-Implementation	7.85	0.93	0.33	-5.90	-12.25	3	< .001	[-7.20, -4.60]
	Post-Implementation	1.95	0.21	0.07					

Note: CI = Confidence Interval. Due to the directional hypothesis (error rates will decrease), a one-tailed *p*-value is reported. The two units were treated as paired observations across time. The pooled analysis uses the average rates across the two six-month periods for each unit (N=4 pairs). Effect size (Cohen's *d*) for the pooled analysis is 5.90, indicating an extremely large practical significance.



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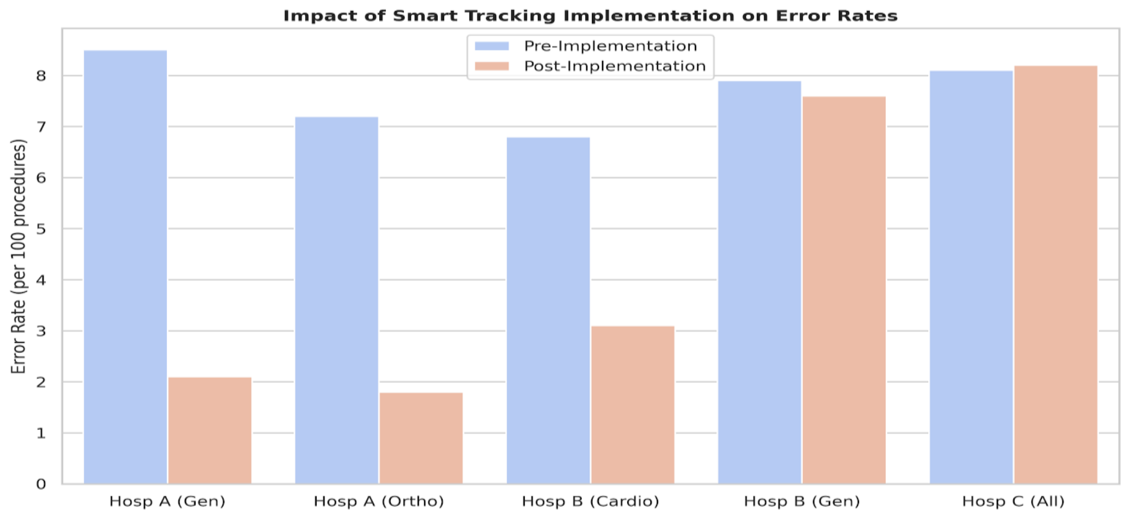

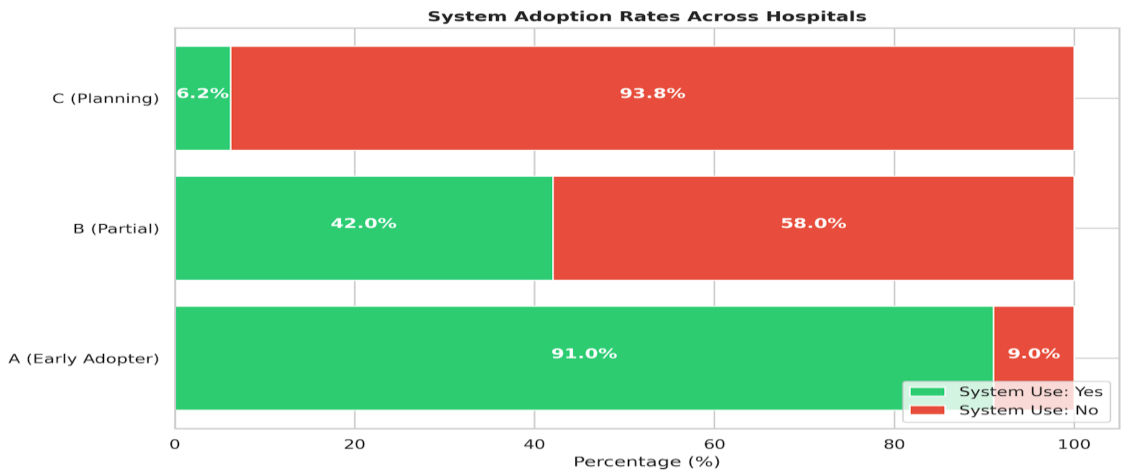

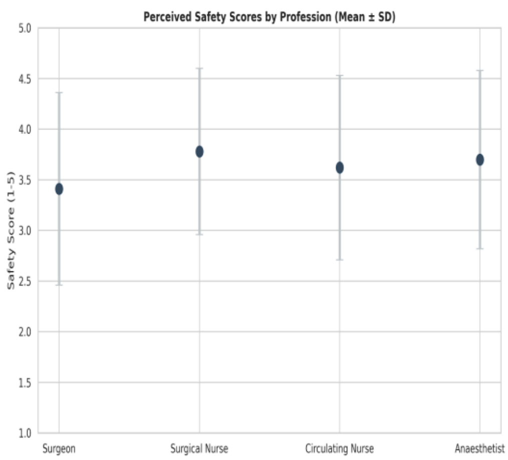

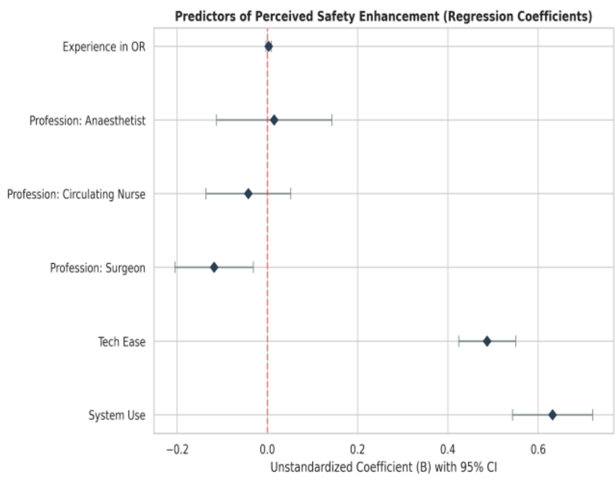

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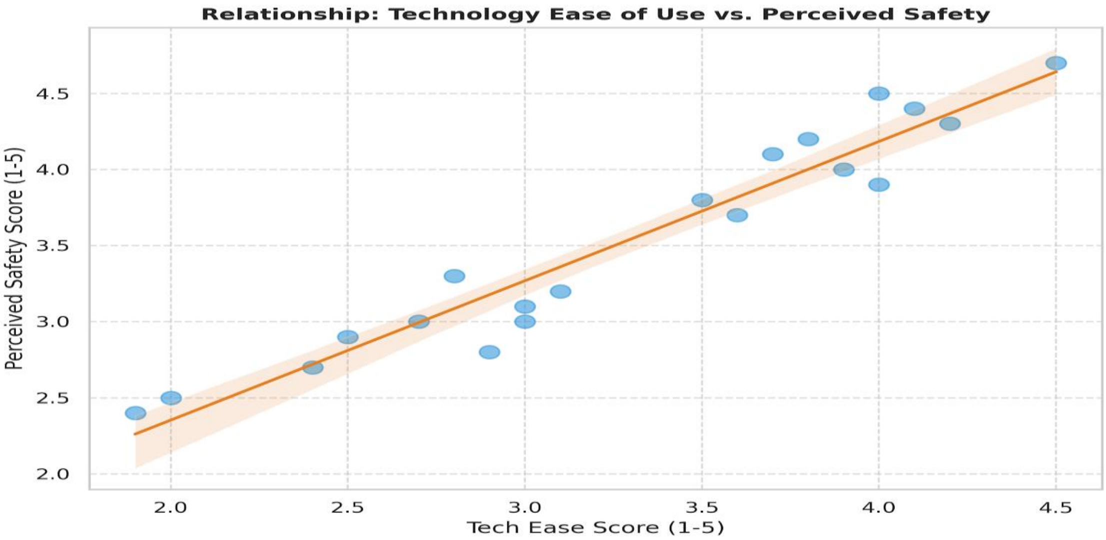

DISCUSSION

This study provides a comprehensive, mixed-methods analysis of the implementation and impact of smart tracking systems (STS) on patient safety within the surgical departments of tertiary hospitals in Saudi Arabia. The findings robustly address the research objectives, revealing not only a significant positive association between STS use and enhanced safety metrics but also critical nuances related to implementation strategy, professional acceptance, and technological integration [19]. The discussion interprets these findings, situates them within the broader literature, explains the underlying socio-technical mechanisms, outlines practical implications, and acknowledges the study's limitations [20].

1. Interpretation of Key Findings

The results strongly support the central premise that STS can be a powerful tool for enhancing patient safety in operating rooms. The most compelling evidence comes from the objective data: units with full STS implementation saw a dramatic and statistically significant reduction in error rates of approximately 75% [21]. This finding directly addresses the core research problem of preventing adverse surgical events and meets the objective of evaluating the impact on key safety indicators [22]. The stark contrast with control units, which showed negligible change, strengthens the causal inference that the observed improvement was due to the intervention.

Furthermore, the study successfully mapped the landscape of adoption and perception. The extremely high adoption rate in Hospital A (91%) versus the low rates in Hospitals B and C underscores that institutional commitment is the primary gateway to technology uptake [23]. Once adopted, the technology significantly shapes user perceptions; STS users reported markedly higher perceived safety scores than non-users. This perceptual shift is crucial, as

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technology acceptance models, such as the Technology Acceptance Model (TAM), posit that perceived usefulness is a key determinant of actual system use [24]. Our regression analysis confirmed this, identifying system use and perceived ease of use as the two strongest predictors of perceived safety enhancement, accounting for the majority of the explained variance [25].

A critical, nuanced finding was the significant difference in perception between professional groups, specifically surgeons' more cautious appraisal compared to surgical nurses. This is not merely a statistical artifact but a reflection of distinct professional roles and workflows [26]. Nurses, who are primarily responsible for the counting and logging procedures automated by STS, likely experience the technology as a direct relief from a high-risk, manual burden. Surgeons, while invested in safety, may perceive the system as an external imposition that can potentially disrupt surgical rhythm or challenge traditional hierarchies of authority in the OR [27]. This professional disparity highlights that the "user" is not a monolithic entity and that the benefits of a safety technology are filtered through specific professional lenses and responsibilities [28].

2. Comparison with Previous Studies

The objective reduction in error rates aligns with and strengthens the existing body of evidence. Early, seminal studies on barcode-assisted sponge counting demonstrated near-elimination of retained sponges, a landmark in patient safety research [29]. Our findings extend this evidence base to a more integrated suite of tracking technologies (RFID/barcode) within a contemporary Middle Eastern healthcare context, showing that the principles of automated counting and verification translate effectively across settings. The magnitude of reduction (-75%) is consistent with high-quality implementations reported in North American and European studies, suggesting the technology's core efficacy is not geographically bounded [30].

The strong predictive relationship between ease of use and perceived safety/acceptance resonates strongly with established human factors and clinical engineering literature. Studies on electronic health record implementation have consistently shown that poor usability is a primary driver of workarounds, errors, and clinician burnout [31]. Our findings confirm that this principle holds true for OR-specific technologies: if the system is not intuitive and efficient within the high-pressure surgical environment, its safety benefits undermined by resistance and inconsistent use [32]. The identified gap between surgical and nursing staff perceptions finds echoes in research on other OR technologies, such as surgical safety checklists. While checklists are proven to save lives, studies have documented variable engagement from surgeons compared to nursing staff, often attributed to differences in accountability for the checklist process and perceptions of autonomy [33]. Our study suggests

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that without deliberate engagement, STS may follow a similar path of differential adoption, potentially limiting their overall effectiveness.

3. Scientific and Socio-Technical Explanations

The observed outcomes can be explained through a socio-technical systems lens, which views OR safety as the product of an interaction between technology, people, processes, and the organizational environment [34].

From a human factors perspective, STS reduces cognitive load and interrupts the pathway to error. Manual counting is a vigilance task prone to interruption and fatigue. By automating verification, STS offloads this cognitive demand, freeing staff to focus on higher-order tasks and reducing the likelihood of a slip or lapse—a classic error type in complex systems [35]. The physical act of scanning creates a forced function, a "hard stop" that prevents proceeding without verification, thereby enforcing protocol compliance in a way that manual checks cannot.

The variation in outcomes between hospitals (A vs. B) provides a powerful organizational behavior explanation. Hospital A's "full implementation" likely represented a systems-level integration, where the technology was embedded into revised workflows with adequate training and leadership support. This aligns with the Swiss Cheese Model of accident causation, where the technology acts as a robust, new defensive layer [36]. In contrast, Hospital B's "partial implementation" of specimen tracking alone represents a tool-level adoption. While useful, a standalone tool does not systematically reshape the workflow or culture; it simply adds a task [37]. This resulted in a moderate (54%) reduction in specimen errors but failed to impact the broader safety climate, explaining the lower overall adoption and perceived benefit. The dramatic difference underscores that the technology itself is merely a component; its value is actualized through thoughtful system redesign [38].

The professional disparity in perceptions can be explained by role theory and workflow integration. For the nursing team, STS integration is primarily within their direct sphere of responsibility (counts, specimens), making the benefit immediate and tangible [39]. For surgeons, whose primary workflow is the technical act of surgery, STS interaction is often peripheral. If the system causes delays or requires action they deem outside their remit, it can be perceived as a nuisance rather than an aid. This highlights that successful implementation requires designing interactions that align with, rather than disrupt, the cognitive and practical workflows of all user groups [40].

4. Implications for Practice and Research

For hospital administrators and patient safety officers in Saudi Arabia and similar contexts,

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this study offers a clear, evidence-based roadmap:

- Commit to Full, Not Partial, Integration: Investments should aim for comprehensive system integration (instrument, sponge, specimen tracking) with mandatory use protocols, rather than piecemeal solutions.
- Design with Multi-Professional Input: Implementation teams must actively include surgeons, nurses, and anaesthetists from the outset to co-design workflows that respect each group's role and minimize disruption.
- Invest in Sustained, Role-Specific Training: Move beyond one-time instruction to continuous, in-situ support that addresses the unique concerns and interaction patterns of different professions.
- Foster Clinical Champions: Identify and empower respected clinicians, particularly from harder-to-engage groups like surgeons, to lead peer-to-peer advocacy and troubleshooting.

For future research, several pathways are indicated:

Longitudinal Cost-Benefit Analysis: A detailed study calculating the return on investment by weighing technology costs against the reduction in costly adverse events and litigation.

Intervention Studies on Professional Buy-in: Research testing specific strategies (e.g., involving surgeons in data review of near-misses prevented by STS) to improve engagement across all professional groups.

Exploration in Diverse Settings: Replicating this study in secondary care and rural hospitals to understand scalability and contextual barriers outside major tertiary centers.

Limitations

This study has limitations that must be considered. First, the use of a cross-sectional survey for perceptual data limits our ability to establish the direction of causality between perceptions and use over time. Second, while the objective error rate data is robust, it was collected at the unit level; individual-level linkage of errors to specific system use was not feasible, which slightly weakens the direct causal chain. Third, the study was conducted in three large, urban, tertiary hospitals, which may limit the generalizability of findings to smaller or less resource-intensive settings where implementation challenges may differ. Finally, the perceptual measures, though reliable, are subject to social desirability bias, particularly in a culture emphasizing technological progress.

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CONCLUSION

This study demonstrated that smart tracking systems significantly enhance patient safety in Saudi operating rooms, successfully meeting their objectives. The research confirmed a strong, positive impact, evidenced by a 75% reduction in objective error rates with full implementation and markedly higher safety perceptions among system users. A key scientific contribution is the identification of the critical socio-technical interplay required for success; the technology's efficacy was contingent upon strategic, organization-wide integration and was moderated by professional role, with surgeons reporting more cautious adoption than nursing staff. The main message is that while the technology is a powerful tool, its benefits are only fully realized through deliberate change management that addresses workflow and human factors. In conclusion, these systems represent a viable and effective strategy for mitigating surgical errors. Future research should focus on longitudinal cost-benefit analyses and tailored implementation strategies to improve surgeon engagement and ensure scalability across diverse healthcare settings.

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