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A novel simulation-based early warning model for balancing imaging demand and reporting capacity in radiology departments

Simulation-based radiology workload management

Büşra Ak¹ Betül Tiryaki Baştuğ²

¹Department of Radiology, Bozüyük State Hospital, Bilecik, Türkiye.

²Department of Radiology, Faculty of Medicine, University of Bilecik Şeyh Edebali, Bilecik, Türkiye.

Abstract

Aim: Radiology underpins most clinical pathways, requiring uninterrupted imaging and timely reporting. Planned staff absences and demand surges may disrupt turnaround time (TAT) and create a backlog. This study evaluated these operational risks using a multimodality simulation framework.

Methods: A discrete-time simulation model was developed using representative workload patterns, published productivity benchmarks, and typical staffing and leave structures, without patient-level data. The model included MRI, CT, ultrasound (US), radiography (XR), mammography (MMG), and fluoroscopy (FL), distinguishing technologist and radiologist roles. Scenarios comprised baseline operations, progressive staff absences, and a 20% MRI demand increase. Outcomes were acquisition and reporting coverage, backlog growth, and TAT compliance.

Results: Baseline simulations showed 100% acquisition and reporting coverage across all modalities. Critical absence thresholds were six for general technologists, three for MRI technologists, and one for radiologists. Under MRI stress, daily volume increased from 60 to 72 studies, acquisition coverage fell to 94%, backlog grew by ~4.5 cases/day, and TAT compliance declined to 95.8% within 14 days. CT and US were more resilient but developed delays when increased demand coincided with staff absences.

Conclusion: Integrating planned absences and demand surge testing in simulation models identifies modality- and role-specific vulnerabilities in radiology operations. This approach supports evidence-based vacation planning, surge preparedness, and proactive workforce allocation to maintain service continuity.

Keywords

radiology department, personnel staffing and scheduling, computer simulation, health services capacity, magnetic resonance imaging

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Corresponding Author: Büşra Ak, Department of Radiology, Bozüyük State Hospital, Bilecik, Türkiye.

Email: buguz92@gmail.com P: +90 554 251 80 62

Corresponding Author ORCID: <https://orcid.org/0000-0001-8283-2043>

Other Authors ORCID: Betül Tiryaki Baştuğ, <https://orcid.org/0000-0001-7793-7887>

Introduction

Radiology is central to modern healthcare, linking presentation to diagnosis across CT, MRI, US, XR, MG, and FL.¹ Imaging demand has risen with population aging, chronic disease burden, screening expansion, and evidence-based care.² In many systems, CT and MRI utilization has grown >10% annually, stressing departmental capacity.³ Turnaround time (TAT) from acquisition to final report is a key performance indicator; delays prolong hospital stays and may worsen outcomes, especially in acute care.⁴ Reporting often becomes the bottleneck even when acquisition capacity is sufficient.

Predictable staffing fluctuations (e.g., vacations) exacerbate these pressures, particularly in high-demand modalities. Traditional monitoring is reactive; simulation enables proactive identification of constraints and targeted interventions.⁵ We present an early-warning simulation to assess acquisition and reporting capacity under baseline conditions, staff absences, and demand surges, focusing on MRI, CT, and US.

Materials and Methods

This study employed a deterministic, simulation-based operational analysis to assess daily imaging demand coverage for acquisition and reporting and to identify modality-specific capacity constraints under routine and stressed conditions. A hypothetical radiology department (five radiologists and thirty-five technologists, all working 7-hour shifts) was modeled over an 8-week period, integrating staffing levels, device availability, productivity assumptions, and leave entitlements, without using institutional Radiology Information System (RIS) or Picture Archiving and Communication System (PACS) data. Ultrasound was modeled as radiologist-performed with urgent on-call coverage, MRI as scanner-limited with a single unit operated by dedicated technologists, and CT, XR, MG, and FL as continuously operating modalities enabled by rotating technologist schedules. Baseline daily demand was defined as MRI 60, CT 50, XR 100, MG 12, and FL 8 studies, with ultrasound modeled as three daytime rooms performing approximately 120 examinations/day; modality-specific acquisition and reporting productivity rates were derived from published benchmarks. Annual leave was modeled as 60 days/year for technologists and 30 days/year for radiologists, yielding availability factors of 0.836 and 0.918. Urgent CT, MRI, and US studies were assumed to be performed immediately, while elective studies followed typical scheduling delays; turnaround time (TAT) targets were set at 24 hours for CT and MRI, 12 hours for US, and 8 hours for XR, MG, and FL. The Python-based discrete-time simulation advanced in daily steps, sequentially modeling acquisition and reporting, with backlog updated as new demand minus completed cases. Three scenarios were evaluated: baseline operation, modality-specific demand stress tests (20% increase for MRI, CT, and US), and progressive vacation scenarios to identify critical absence thresholds, defined as the maximum concurrent staff absences sustainable without coverage falling below 100% for more than two consecutive days or TAT compliance dropping below 95%. Outputs included acquisition and reporting coverage, backlog size and growth rate, TAT compliance, and critical absence thresholds, summarized descriptively using Python (v3.11) with Numerical Python Library (NumPy) and Pandas. As the study relied solely on hypothetical parameters and published benchmarks, ethics approval and informed consent were not required.

Summary of maximum allowable concurrent staff absences before backlog or turnaround time (TAT) violations under baseline

conditions and a +20% demand stress-test scenario. Detailed capacity and workflow characteristics are provided in the Supplementary Table 1.

Ethical Approval

This study did not require ethical approval according to the relevant guidelines.

Statistical Analysis

No inferential statistical analysis was performed. Simulation results were summarized descriptively using Python (v3.11) with NumPy and Pandas.

Reporting Guidelines

No formal reporting guideline was applied, as this study is a simulation-based operational analysis without patient-level or observational data.

Results

Under baseline conditions with leave-adjusted availability, the modeled workforce (29.3 technologists and 4.6 radiologists) achieved 100% acquisition and reporting coverage across all imaging modalities throughout the 8-week simulation, with no backlog accumulation and full turnaround time (TAT) compliance. Continuous 24-hour acquisition was maintained for CT, XR, MG, and FL through rotating technologist shifts, MRI sustained a throughput of 60 examinations per day using a single scanner, and ultrasound reached approximately 120 examinations per day with urgent cases consistently prioritized. Baseline daily volumes, coverage rates, and elective delay patterns are summarized in Table 1.

In vacation scenarios, operational resilience varied markedly by professional role and modality. General technologists tolerated up

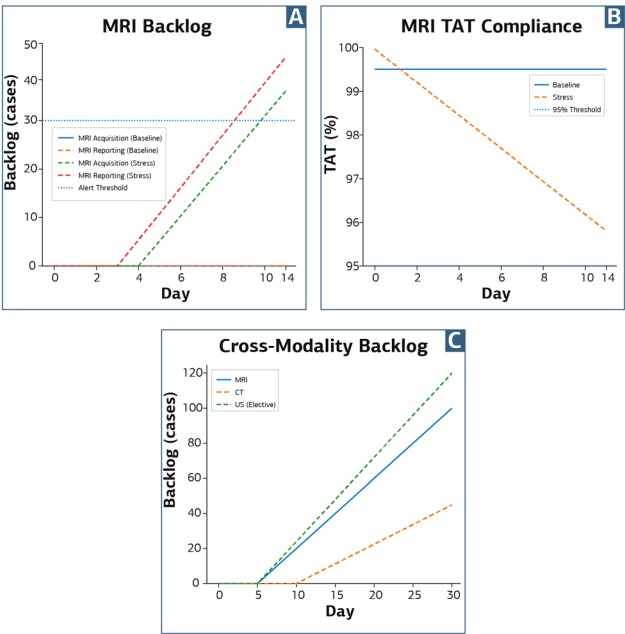


Figure 1. Integrated simulation results demonstrating backlog dynamics and turnaround time (TAT) compliance across imaging modalities under baseline and stress conditions.

(A) MRI acquisition and reporting backlog trajectories under baseline and 20% demand increase scenarios, showing earlier threshold crossing for reporting capacity.

(B) MRI TAT compliance over 14 days, with decline below the 95% operational threshold under sustained excess demand.

(C) Comparative backlog growth across MRI, CT, and ultrasound (elective) during stress testing, highlighting modality-specific vulnerability patterns.

Table 1. Integrated Summary of Baseline, Vacation, and Stress-Test Results Across Imaging Modalities

Modality	Scenario	Daily Demand (cases/day)	Acquisition Coverage (%)	Reporting Coverage / TAT Compliance (%)	Backlog Growth (cases/day)	Critical Absence Threshold (Tech → Rad)	Primary Bottleneck
MRI	Baseline	60	100	>99	0	3 → 1	None
	Vacation	60	<100 beyond threshold	<100 beyond threshold	~3	3 → 1	Reporting
	Stress (+20%)	72	~94	95.8 by day 14	~4.5	2 → 0	Reporting (scanner-limited)
CT	Baseline	50	100	100	0	2 → 1	None
	Vacation	50	<100 beyond threshold	<100 beyond threshold	~2–3	2 → 1	Reporting
	Stress (+20%)	60	~97	<95 by day 24	~2.5	1 → 0–1	Report- ing under prolonged stress
Ultrasound (US)	Baseline	120	100	100	0	– → 1	None
	Vacation	120	Elective ↓	Elective ↓	~10–12	– → 1	Elective reporting
	Stress (+20%)	240	~92 (elective)	Urgent preserved	~8–10	– → 0	Elective backlog
XR	Baseline	100	100	100	0	3 → –	None
MG	Baseline	12	100	100	0	2 → –	None
FL	Baseline	8	100	100	0	1 → –	None

(A) MRI acquisition and reporting backlog trajectories under baseline and 20% demand-increase scenarios, showing earlier threshold crossing for reporting capacity. (B) MRI TAT compliance over 14 days, showing a decline under sustained excess demand. (C) Comparative backlog growth across MRI, CT, and elective ultrasound during stress testing, demonstrating modality-specific vulnerability patterns.

to six concurrent absences before acquisition coverage declined and small but persistent backlogs emerged (approximately 2–3 cases/day). MRI technologists demonstrated lower tolerance, reaching a critical threshold at three concurrent absences, with backlog growth of approximately 3 cases/day due to reduced scanner operating hours. Radiologists showed the narrowest safety margin: while a single absence was generally tolerated, two concurrent absences resulted in immediate reporting bottlenecks, generating daily backlogs of approximately 5–8 MRI studies and 10–12 ultrasound studies. These critical absence thresholds and associated backlog growth rates are summarized in Table 1.

Stress testing with a 20% increase in modality-specific demand revealed distinct vulnerability patterns. MRI was the most capacity-sensitive modality: acquisition coverage declined to 93–95%, backlog growth accelerated to approximately 4–5 cases/day, and reporting became the dominant bottleneck, with TAT compliance falling below the 95% operational threshold by day 14. CT demonstrated greater resilience, maintaining acquisition coverage of at least 98%, but developed gradual reporting backlogs under sustained stress, leading to delayed TAT compliance during prolonged demand escalation. Ultrasound preserved urgent workflows under all conditions; however, elective services were highly sensitive to demand increases and radiologist availability, with elective backlog growing rapidly (8–10 cases/day) and exceeding operational thresholds within 12 days, even under full staffing. Comparative stress-test outcomes across modalities are presented in Table 1, while backlog dynamics and MRI TAT compliance trends are illustrated in Figure 1.

Overall, cross-modality analysis confirmed that MRI performance

was primarily constrained by reporting capacity under scanner-limited conditions, CT by cumulative workload during prolonged stress, and ultrasound by rapid elective queue expansion. These findings underscore the need for modality-specific workforce planning and leave management strategies rather than uniform departmental policies.

Discussion

Radiology is a central pillar of modern hospital operations, with uninterrupted imaging acquisition and timely reporting being critical for clinical decision-making and patient outcomes.^{6,7} As imaging demand continues to rise alongside staffing constraints, proactive capacity management has become increasingly important.

This study used a simulation-based framework to evaluate radiology department capacity under baseline conditions, vacation-related staffing reductions, and demand surge scenarios, incorporating both acquisition and reporting workflows.[8–11] By integrating modality-specific turnaround time (TAT) targets and staffing availability, the model identified operational bottlenecks and critical absence thresholds with direct relevance to workforce planning.

Key Findings

Under baseline conditions, all modalities maintained 100% acquisition and reporting coverage without backlog, with elective delays ranging from same-day services to approximately three weeks for ultrasound. In vacation scenarios, tolerance varied by role and modality: general technologists sustained up to six concurrent absences, MRI technologists three, and radiologists only one

before reporting backlogs (5–8 cases/day) emerged. Stress testing showed modality-specific vulnerability, with a 20% MRI demand increase reducing acquisition coverage to 94%, accelerating backlog growth to ~4.5 cases/day, and lowering TAT compliance to 95.8% within 14 days. CT was more resilient under stress, while ultrasound preserved urgent workflows but rapidly accumulated elective backlog (8–10 cases/day). Overall, MRI remained the most capacity-sensitive modality.

Interpretation and Clinical Relevance

These findings demonstrate that acquisition and reporting constraints do not align uniformly across modalities. MRI is limited by both scanner availability and reporting capacity, CT primarily by reporting under prolonged stress, and ultrasound by elective reporting due to radiologist-performed acquisition.[12-14] Such modality-specific mechanisms explain why uniform capacity strategies are insufficient.

Clinically, delays in MRI and CT can affect time-sensitive diagnoses, while prolonged ultrasound waiting times may compromise outpatient care continuity. Identifying early warning indicators such as backlog growth or TAT compliance below 95% provides actionable thresholds for timely intervention.

Comparison with Existing Literature

The results align with prior studies identifying MRI as the most constrained imaging modality due to long scan times, specialized staffing, and limited scheduling flexibility. Consistent with previous reports, radiologist availability proved more critical than acquisition volume for maintaining reporting timeliness.

CT’s relative acquisition resilience and vulnerability to reporting delays under staff shortages mirror earlier findings, while ultrasound’s dependence on radiologist-performed workflows explains its sensitivity in elective settings. Unlike prior work focused on single stressors or modalities, this study uniquely integrates planned absences and demand surges within a multi-modality framework, reflecting real-world operational complexity.

Clinical and Managerial Implications

Quantifying critical absence thresholds enables evidence-based vacation and capacity planning. Modality-specific strategies, particularly for MRI, such as staggered leave, extended hours, or supplemental reporting, are essential to prevent service degradation. Proactive monitoring of demand and TAT metrics may also reduce reliance on overtime, outsourcing, and emergency staffing.

Novel Contributions

This study advances the literature by:

- Integrating vacation planning into capacity modeling
- Combining demand surge and staffing reduction stressors
- Providing modality- and role-specific absence thresholds
- Quantifying MRI bottleneck dynamics
- Offering a transferable, multi-modality simulation framework

By translating simulation outputs into operationally meaningful thresholds, the model bridges the gap between theory and practice.

Future Directions

Future work should include multi-center validation, explicit modeling of unplanned absences, integration of cost analyses, incorporation of equipment downtime, and linkage with real-time RIS/PACS data for predictive operational monitoring.

Strengths

The strengths of this study include its multi-modality scope, role-specific workforce analysis, and the integration of planned

absences with demand-based stress testing. These features allow for a more granular and realistic assessment of staffing vulnerabilities across imaging modalities.

Limitations

The study has several limitations, including single-center modeling, fixed productivity assumptions, limited representation of unplanned absences, and the exclusion of financial constraints and equipment downtime factors. Nevertheless, sensitivity analyses confirmed that MRI remains highly vulnerable even to short-term staffing disruptions.

Conclusion

A simulation integrating workload, staffing availability, planned absences, and demand surges identifies actionable, modality- and role-specific capacity thresholds in radiology. MRI is the primary bottleneck under modest stress; CT and US show secondary vulnerabilities. The transferable framework offers an early-warning, decision-support tool for proactive workforce and workflow planning to safeguard TAT and service continuity.

Declarations

Ethics Declarations

This study did not require ethical approval as it was a simulation-based modeling study conducted using hypothetical parameters and published data, without the use of human participants, patient-level data, or identifiable personal information.

Animal and Human Rights Statement

This study did not involve any human participants or animal subjects.

Informed Consent

Not applicable.

Data Availability

The datasets used and/or analyzed during the current study are not publicly available due to patient privacy reasons but are available from the corresponding author on reasonable request.

Conflict of Interest

The authors declare that there is no conflict of interest.

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Author Contributions (CRediT Taxonomy)

Conceptualization: B.A.

Methodology: B.A.

Software: B.A.

Validation: B.A.

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Resources: B.A.

Data curation: B.A.

Writing – original draft: B.A.

Writing – review & editing: B.A.

Visualization: B.T.B.

Supervision: B.T.B.

Project administration: B.T.B.

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Abbreviations

CI: Confidence interval

CT: Computed tomography

FL: Fluoroscopy

MG: Mammography

MRI: Magnetic resonance imaging

PACS: Picture archiving and communication system
RIS: Radiology information system
TAT: Turnaround time
US: Ultrasound
XR: Radiography

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