Radiology

ORIGINAL RESEARCH • HEALTH POLICY AND PRACTICE

# Cumulative Effect of Targeted Interventions on Radiologist Recommendations for Additional Imaging

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See also the editorial by Russell in this issue.

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***Background:*** Ambiguous or unnecessary radiologist recommendations for additional imaging (RAIs) can lead to excessive imaging use and diagnostic errors.

***Purpose:*** To determine the cumulative impacts of multifaceted technology-enabled interventions aimed at optimizing RAI on RAI rate, actionability, and resolution over an 8-year period.

***Materials and Methods:*** In this retrospective cohort study, conducted from January 2015 to December 2022, radiology reports from two tertiary hospitals (study site and control site) were analyzed. A series of quality improvement interventions, including radiologist education, electronic communication tools for tracking RAIs, and performance reports, were implemented at the study site but not at the control site. The RAI rate trend over time was compared between the sites using linear regression. Mixed-effects logistic regression was performed to assess the intervention impact on the RAI rate. RAI actionability and resolution were compared between the sites using the Fisher exact test. *P* values were corrected using the Bonferroni method.

***Results:*** Among 7 502 521 total radiology reports (1 323 459 patients) (study site, 3 608 977 reports and 660 051 patients; control site, 3 893 544 reports and 690 115 patients), the RAI rate of the study site decreased by 44%, from 10% (8202 of 81 586) to 5.6% (8972 of 159 599), but remained unchanged at the control site, at 10.9% (8757 of 80 030) vs 11% (16 978 of 153 711) (regression coefficient, −0.09; 95% CI: −0.1, −0.09; $P < .001$). RAI rates declined with each successive intervention at the study site ($P < .001$), with regression coefficients decreasing progressively from −0.12 (95% CI: −0.14, −0.10) for the initial intervention to −0.81 (95% CI: −0.83, −0.78) for the final intervention. Recommendation actionability at the study site increased 7.6-fold (from 5.6% [19 of 340] to 42.3% [144 of 340]; $P < .001$) but remained unchanged at the control site (from 15.0% [51 of 340] to 13.8% [47 of 340]; $P = .73$). Actionable RAIs were more frequently resolved at the study site than at the control site (84.7% [122 of 144] vs 59.6% [28 of 47]; $P < .001$).

***Conclusion:*** Multifaceted interventions to optimize RAI improved the rate, actionability, and resolution of RAI.



*Supplemental material is available for this article.*

Diagnostic errors (ie, missed or delayed diagnoses) affect approximately 12 million Americans and may account for 40 000–80 000 preventable deaths annually (1,2). Imaging is one of the largest sources of diagnostic data; more than 349 million diagnostic imaging examinations are performed annually in the United States (3). More than 10% of radiology reports for diagnostic examinations contain a recommendation for additional imaging (RAI) to assess unexpected, unexplained, or uncertain findings (4–6). However, RAI rates vary substantially, even among subspecialty-trained radiologists in the same practice (5,7). Ultimately, between one-quarter and two-thirds of RAIs may not be acted on by referring providers (8–13) owing to reasons including patient clinical factors and preferences that are unknown to the radiologist at the time of examination interpretation, and a lack of systems to ensure timely performance of clinically necessary RAIs. Lack of timely performance may increase the risk of diagnostic error and patient harm. Concurrently, unnecessary recommendations can result in both overuse of imaging and cascades of care, which can increase costs (14).

At a large hospital within a multisite health system, a series of multifaceted technology-enabled interventions designed to improve the actionability and clarity of RAIs were implemented, and a safety net team was created (15) to help ensure the timely performance of clinically necessary RAIs. This study aimed to assess the cumulative impacts of these interventions on the RAI rate, actionability, and resolution for 8 years at the study institution compared with a control site hospital in the same health care system that maintained its existing RAI standard-of-care practices during the study period.

## Materials and Methods

### Study Sites, Design, and Cohort

This retrospective study was conducted from January 1, 2015, to December 31, 2022, at two academic urban tertiary care hospitals within the same large multisite health care system. It was exempted from institutional review board approval with waivers of the requirement to obtain patient consent and was conducted in compliance with Health Insurance Portability and Accountability Act regulations.

The diagnostic radiology reports generated during the study period across the abdominal, cardiovascular, chest, emergency, musculoskeletal, neuroradiology, nuclear medicine, and US (study site only; the control site had no US division) divisions

## Abbreviations

ARRC = Addressing Radiologist Recommendations Collaboratively, EHR = electronic health record, RAI = recommendation for additional imaging

## Summary

Multifaceted interventions to optimize radiologist recommendations for additional imaging, including education, electronic communication tools for recommendation tracking, and performance reports, reduced recommendation rates, improved actionability, and enhanced clinical follow-through.

## Key Results

- In a retrospective cohort study of 7 502 521 radiology reports, the rate of recommendations for additional imaging (RAIs) decreased by 44% at the study site that received interventions to optimize RAIs but remained unchanged at the control site receiving no interventions (regression coefficient, −0.09; *P* < .001).
- RAI actionability increased 7.6-fold (*P* < .001) at the study site but remained unchanged at the control site (*P* = .73).
- Actionable RAIs were performed or scheduled more frequently at the study versus the control site (*P* < .001).

were eligible for this study. Obstetrics (not interpreted by radiologists) and breast (which uses Breast Imaging Reporting and Data System recommendation reporting) divisions were not included. To identify reports that included RAI, a validated artificial intelligence model was used (*https://github.com/NooshinAbbasi/Recommendation-for-Additional-Imaging*) (16). The language that was considered to indicate RAI was any phrase that may convey an RAI, either explicitly (eg, "recommend short interval follow-up") or implicitly (eg, "bears watching/monitoring on future studies").

### Interventions

Radiology departmental leadership identified RAIs as a quality improvement opportunity, given the variation in RAI rates (5). Multifaceted, technology-enabled interventions were subsequently implemented at the study site (Table 1); no interventions were implemented at the control site. In intervention 1, implemented in January 2017, meetings were held to educate radiologists about interradiologist variation in RAI rates and to avoid ambiguous language to help create actionable RAIs.

In intervention 2, beginning in March 2018, an electronic closed-loop communication and tracking tool to send RAIs to referring providers was piloted in thoracic radiology for incidental pulmonary nodules (17). The referring provider could agree that the RAI was clinically necessary or reject or modify the RAI. A safety net team consisting of six individuals, totaling 2.2 full-time equivalents, helped ensure bidirectional communication between radiologists and referring providers and facilitated the timely performance of RAIs that were agreed to be clinically necessary (15).

In intervention 3, two feedback reports were disseminated to each attending radiologist; reports contained their RAI rates relative to those of their subspecialty peers for 1 year (December 2018) and 3 years (July 2019). Because radiologists were unlikely to accurately estimate their own RAI probability (18), these reports aimed to educate the radiologists in variation in RAI rates and their own RAI rates versus those of their peers.

**Table 1: Details of the Interventions at the Study Site**

| Intervention | Description |
|---|---|
| 1. Radiologist education (start date: January 2017) | Radiologists were educated about the existing variation in interradiologist recommendations for additional imaging (RAI) rates and the role of avoiding ambiguous language to help create actionable RAIs. Education and group discussion occurred in several faculty meetings with the Radiology Department Chair and the health care system Vice Chair of Quality. |
| 2. Pilot program for RAI for incidental pulmonary nodules (start date: March 2018) | An electronic closed-loop communication tool and a safety net team were pilot tested in the Thoracic Division to communicate and track RAIs for incidental pulmonary nodules to resolution. The tool supplemented the standard radiology report availability in the electronic health record. Tool use was voluntary, but when used, radiologist entry of RAI rationale, imaging modality, and timeframe were required. Notified electronically, the referring provider could agree that the RAI was clinically necessary or reject or modify the RAI. A safety net team provided outreach to patients or referring providers to help ensure timely performance of clinically necessary RAIs. The results of this pilot were shared with all study site radiologists at several faculty meetings in anticipation of broad departmental expansion. |
| 3. RAI feedback reports (start date: December 2018) | Feedback reports were developed and distributed to educate radiologists on the interradiologist variation in RAI rates and their own individual RAI rates versus those of their peers in their subspecialty division. This intervention was conducted in two phases with reporting on the radiologist's performance over the previous 1-year period in phase 1 (December 2018) and over a 3-year period in phase 2 (July 2019). |
| 4. Addressing Radiologist Recommendations Collaboratively (ARRC), monthly RAI reports, and diagnostic certainty scale (start date: October 2019) | The electronic closed-loop communication and tracking tool and the safety net team from intervention 2 were expanded across the Radiology Department for all RAIs for all clinical conditions except breast imaging. This initiative—ARRC—was led by a multidisciplinary expert panel co-chaired by the chief medical officer and radiology vice chair for quality and safety of the institution. Members of the committee included vice chairs of quality from multiple hospital departments and leaders in the department of quality and safety.<br>In addition, use of a diagnostic certainty scale was encouraged to improve standardized communication in radiology reports. The diagnostic certainty scale language framework was created through input from a multidisciplinary team consisting of radiologists and quality and safety officers from other clinical departments.<br>Although strongly encouraged, use of the ARRC tool and diagnostic certainty scale was voluntary. |

**Table 2: Characteristics of the Study Cohort by Site**

| Parameter | Study Site | Control Site |
|---|---|---|
| Radiologist variables | | |
| Trainee presence-to-all ratio | 0.34 | 0.42 |
| Present | 1 068 428 | 1 428 893 |
| All | 3 137 445 | 3 367 388 |
| Female-to-male ratio | 1.01 | 0.48 |
| Female | 66 | 80 |
| Male | 65 | 167 |
| Years in practice (*n*) | 10.6 ± 11.7 | 7.1 ± 10.7 |
| Patient variables | | |
| Mean age (y) | 59.2 ± 17.8 | 58.2 ± 18.7 |
| Female-to-male ratio | 1.27 | 1.03 |
| Female | 1 756 395 | 1 714 823 |
| Male | 1 381 050 | 1 652 487 |
| Imaging variables | | |
| Modality | | |
| Radiography | 1 382 934 | 1 604 427 |
| CT | 893 010 | 891 924 |
| MRI | 473 015 | 417 511 |
| Gamma/PET | 75 094 | 98 253 |
| US | 270 911 | 313 134 |
| Fluoroscopy | 42 481 | 31 262 |
| Subspecialty division | | |
| Abdominal | 505 168 | 638 625 |
| Cardiovascular | 33 666 | 150 958 |
| Chest | 728 329 | 703 731 |
| Emergency department | 709 421 | 619 144 |
| Musculoskeletal | 538 844 | 641 423 |
| Neurology | 384 492 | 524 714 |
| Nuclear medicine | 79 215 | 78 245 |
| US | 158 310 | … |

Note.—Unless otherwise indicated, data are numbers of radiologic reports. Mean data are ± SDs. Detailed information is provided on post–electronic health record implementation data. Patient variables are presented on the basis of unique reports.

In intervention 4, beginning in October 2019, intervention 2 was expanded to include all radiology divisions and RAIs for all clinical conditions in the Addressing Radiologist Recommendations Collaboratively (ARRC) initiative (15). ARRC tool use was voluntary but strongly encouraged and monitored by departmental leadership. Beginning in January 2021, radiologists received monthly reports featuring their number and rate of RAIs compared with those of their subspecialty peers, and meetings were held to review RAI trends. Radiologists were also encouraged to use language from a diagnostic certainty scale framework to convey their level of diagnostic uncertainty or certainty rather than commonly used (19) and varied terminology or vague recommendation language, such as “follow-up as clinically indicated.” The specific terms and scale method were published previously (20).

## Data Collection

Eligible radiology reports were extracted from the Research Patient Data Registry. After implementing an electronic health record (EHR) system (Epic Systems) on July 1, 2016, additional patient, radiologist, and modality variables were collected for reports generated from July 1, 2016, to December 31, 2022. The complete dataset (January 1, 2015, to December 31, 2022) was used to analyze RAI trends over time; analyses requiring more detailed variables were conducted using the subset acquired after EHR implementation.

## Classifying RAIs

A validated taxonomy (21) was used to classify RAIs on the basis of five attributes: *complete*, the RAI language contains the recommended imaging modality, time frame, and rationale; *ambiguous*, the language is equivocal or vague; *conditional*, the language contains a qualifier; *multiplicity*, the RAI contains multiple options without delineating the best option; and *alternate*, the RAI is dismissive of the ordered examination in favor of a different examination. An RAI could be classified with more than one attribute. An actionable RAI was defined as complete, unambiguous, unconditional, and without multiplicity or alternate language (21). Resolved RAIs were defined as those that were either completed or scheduled for future performance.

## Outcome Measures

The co-primary outcome measures were the rate and actionability of RAIs. The RAI rate is the percentage of reports with an RAI out of all reports in the study period; RAI actionability is the percentage of reports with RAI defined as actionable. RAI rates and RAI actionability from the study and control sites, covering the first 3 months and last 3 months of the study period after EHR implementation, were compared. The resolution rate of RAIs from the last 3 months of the study period, comparing the study and control sites, was also assessed.

## Statistical Analysis

Study cohort characteristics, encompassing radiologist-, patient-, and imaging-related variables, were evaluated. A linear regression model was used to compare the trends in RAIs between the institutions. A $\chi^2$ test was performed to compare the average RAI rate across different intervention phases at the study site.

Random effects included subspecialty divisions and radiologists nested within subspecialty divisions. The impact of interventions performed at the study site was assessed with institution-to-intervention interaction terms, and the control site was the reference group. To adjust for potential confounding, patient- and imaging-related variables previously associated with the presence or absence of RAI (ie, patient age, sex, and imaging modality) (5) were included in the model as covariates. A multivariable mixed-effects logistic regression model with a logit link function was constructed to determine the relationships between individual interventions and radiologist-related variables and the likelihood of RAI.

To evaluate the effectiveness on RAI actionability, four sets of 340 radiology reports ($n$ = 1360) containing RAI were randomly selected, two sets each from the study and control sites, covering the first 3 months and last 3 months of the study period after implementation of EHR. The sample size was determined on the basis of previous power calculations on the taxonomy (21), with a minimum of 335 reports to detect a 25% difference between groups using a one-sided Fisher exact test, where $P < .05$ was considered to indicate statistical significance, with a power of 0.9. For the study site, the two sets were randomly selected from all reports containing RAI during the time periods. To ensure that any observed between-institution differences were not driven by heterogeneity in language used by radiology subspecialty practices, random sampling was performed at the control site to extract the same proportion of subspecialty divisional reports as what appeared in the sets of the study site. The 1360 reports were scored for each taxonomy attribute by two independent radiologist annotators (N.A. and J.P.G., each with 4 years of posttraining experience) who reviewed the report texts but were blinded to other clinical or imaging data. Scores were determined independently, and there was 100% agreement between the annotators.

To determine whether RAI actionability resulted in a greater likelihood of RAIs being resolved, the EHRs for the two sets obtained from the last 3 months of the study period (one set each from the study and the control site, with ≥4 months elapsed since RAI was generated) were reviewed, and the percentages of resolved RAIs in both the actionable and nonactionable groups were evaluated.

Data analysis was performed using software (Matlab, version 2022a, MathWorks; RStudio, version 1.1.383, RStudio Team) within R software (version 4.2.1; R Foundation for Statistical Computing). Regression analysis $P$ values were corrected using the Bonferroni correction method (22) to account for multiple comparisons. $P < .05$ was considered to indicate statistical significance.

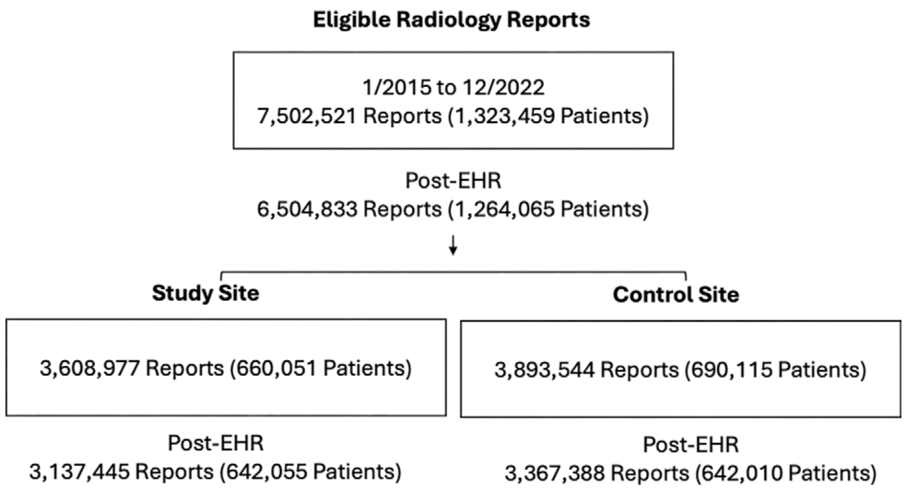


**Figure 1:** Flow diagram shows eligible radiology reports, both overall and by site. Post-EHR (electronic health record) refers to data collected after the implementation of the EHR on July 1, 2016.

## Results

### Cohort Characteristics

A total of 7 502 521 eligible diagnostic radiology reports generated during the 8-year study period for 1 323 459 patients were collected (Fig 1). Of these reports, 6 504 833 were generated after implementation of EHR (3 137 445 generated by 131 radiologists from the study site and 3 367 388 generated by 247 radiologists from the control site). Imaging, patient, and radiologist characteristics of the cohort after implementation of EHR are in Tables 2, S1, and S2.

### RAI Rates

Changes in RAI rates over time are presented in Figure 2. In the first 3 months, 10.0% of the reports at the study site contained at least one RAI, and the RAI rate was 5.6% in the last 3 months, representing a 1.4% quarterly and 44% overall decline in the RAI rate during the study period. However, the percentage of reports containing RAIs at the control site remained unchanged over the 8 years (10.9% in the first 3 months and 11.0% in the last 3 months of the study).

The regression model showed a reduction in RAI at the study site compared with that at the control site (regression coefficient, −0.09; 95% CI: −0.1, −0.09; $P < .001$). Changes in RAI rates per radiology subspecialty division and imaging modality are depicted in Figure S1.

The multivariable mixed-effects logistic regression analysis showed a reduction in the RAI rate with each successive intervention at the study site, with coefficients ranging from −0.12 (95% CI: −0.14, −0.10) for intervention 1 to −0.81 (95% CI: −0.83, −0.78) for intervention 4 ($P < .001$ for each intervention). Statistical results for all interventions are summarized in Table 3.

Per logistic regression analysis (Table 3), increased radiologist years of practice (coefficient, −0.02; 95% CI: −0.02, −0.01; $P < .001$) had a small but statistically significant association with lower RAI rates. Conversely, trainee presence during report generation was associated with higher RAI rates (coefficient, 0.16; 95% CI: 0.15, 0.16; $P < .001$). There was no evidence of an association between the sex of the radiologist and the likelihood of RAI ($P = .71$).

### RAI Actionability

RAI completeness increased at both the study site (from 7.3% to 43.2%; $P < .001$) and the control site (from 21.4% to 32.0%; $P = .001$) between the first 3 months and last 3 months of the post-EHR implementation study period (Table 4). RAI actionability increased at the study site (from 5.6% to 42.3%; $P < .001$) but remained unchanged at the control site (from 15.0% to 13.8%; $P = .73$). Furthermore, RAI ambiguity declined at the study site (from 64.7% to 38.5%; $P < .001$) but increased at the control site (from 56.1% to 70.0%; $P < .001$). The percentage of RAIs classified as multiplicity or alternate also decreased from the first to the last quarter at the study site ($P = .02$ and $P < .001$, respectively) but not at the control site.

### RAI Resolution

The percentage of RAIs that were resolved was greater for actionable RAIs than for nonactionable RAIs (Table S3). At the study site, 84.7% of actionable RAIs were resolved, whereas 50.5% of nonactionable RAIs were resolved ($P < .001$). At the control site, 59.6% of actionable RAIs were resolved and 43.3% (127 of 293) of nonactionable RAIs were resolved ($P = .04$). Finally, actionable RAIs were resolved at a 30% higher rate at the study site than at the control site (84.7% [122 of 144] vs 59.6% [28 of 47]; $P < .001$).

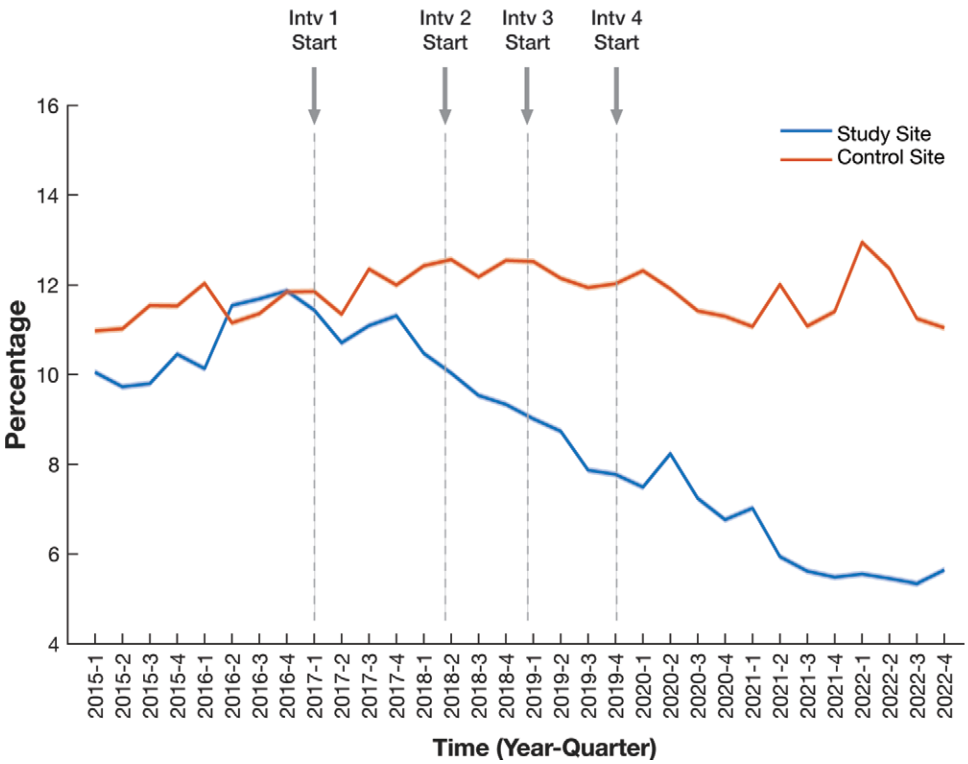


**Figure 2:** Graph shows rate of recommendations for additional imaging in radiology reports over time at the study and control sites during the 8-year study period. Intv = intervention.

**Table 3: Predictors of Recommendations for Additional Imaging in Radiology Reports from Mixed-Effects Logistic Regression**

| Parameter | Regression Coefficient | *P* Value |
|---|---|---|
| Intervention effect (study site) | | |
| Preintervention (control site) | Reference | Reference |
| Intervention 1 | −0.12 (−0.14, −0.10) | <.001 |
| Intervention 2 | −0.33 (−0.35, −0.30) | <.001 |
| Intervention 3 | −0.46 (−0.48, −0.43) | <.001 |
| Intervention 4 | −0.81 (−0.83, −0.78) | <.001 |
| Radiologist variable | | |
| Trainee, absent | Reference | Reference |
| Trainee, present | 0.16 (0.15, 0.16) | <.001 |
| Female | Reference | Reference |
| Male | −0.17 (−0.33, −0.004) | .71 |
| No. of years in practice | −0.02 (−0.02, −0.01) | <.001 |

Note.—Data in parentheses are 95% CIs. *P* values were calculated using mixed-effects logistic regression models. Bonferroni correction was applied to adjust for multiple comparisons.

## Discussion

Compared with a concurrent control site within the same health care system, multifaceted technology-enabled interventions at a large academic medical center led to a 44% reduction in the recommendation rate for additional imaging (RAI) during an 8-year period, a 7.6-fold increase in actionable RAIs, and a 30% higher resolution rate of actionable RAIs. The RAI rate and actionability remained unchanged at the control site. Building on our previous results of a 25% reduction in RAI rates in thoracic radiology (23), these findings demonstrate the impact of interventions across multiple radiologic subspecialties and modalities, and suggest the potential to increase follow-through on actionable RAIs to improve patient safety by reducing diagnostic errors. Furthermore, this initiative may help streamline imaging practices and contribute to more judicious use of imaging resources.

The 7.6-fold increase in actionable RAIs, driven primarily by implementing a closed-loop communication tool, underscores another novel advancement in our initiative. When combined with the 44% reduction in RAI rate, this increase in actionable RAIs represents a substantial reduction in ambiguous, conditional, incomplete, and otherwise nonactionable RAIs for referring providers to consider. Previous strategies to improve RAI actionability have included structured reporting and clinical decision support for radiologists; however, the impact of these strategies was modest. In a recent analysis, 62% of RAIs documented as free text in a discrete subheading of a structured radiology report lacked a follow-up time frame (24), an attribute associated with a higher rate of RAI resolution (25). The ARRC tool used in our study required entering an RAI time frame, with tool use strongly encouraged and monitored by departmental leadership.

Nearly 85% of clinically necessary actionable RAIs across care settings (outpatient, inpatient, and emergency departments) were resolved at the study site, which is higher than that reported in most prior studies (11–13,26,27). The ARRC tool enabled explicit radiologist-to–referring provider interaction for every RAI, supplementing the typical radiology standard, a factor associated with a higher rate of follow-up resolution (12,24). The 7.6-fold increase in actionable RAIs in our study is also a major contributor to the higher RAI resolution rate. Actionable RAIs, without conditional language or other contingencies, are resolved at a higher rate than are conditional or nonactionable RAIs, as observed at our control site and previously reported (12,13,24). Finally, our high RAI resolution rate is most likely due to the "system" design of the ARRC initiative. Foundational elements included leadership engagement, performance monitoring and feedback, the requirement of the ARRC tool to create actionable RAIs, explicit referring provider interaction with each RAI to establish RAI clinical necessity by incorporating patient clinical factors and preferences, and the use of a safety net team for provider and patient outreach and care coordination to close gaps in care. Prior studies have shown the benefits of safety net structures and processes to enhance the resolution of RAIs for pulmonary nodules (28,29), and RAIs for incidental findings in the emergency department (30). Prior work (15) has also shown that a safety net team, as part of a technology-enabled quality and safety infrastructure, can generate revenue by increasing the completion rate of clinically necessary follow-up imaging, which can entirely fund the safety net team.

To expand the potential patient safety benefits of this work, the full complement of the interventions in place at the study site at the end of the study period is being extended across the entire health care system. We are also assessing whether generative artificial intelligence tools can facilitate the workflows in this program. For example, in another study from our center (31), we have demonstrated the accuracy of ChatGPT (OpenAI) large language models for extracting details of RAIs from the free-text impressions of radiology reports, which may ultimately help reduce workflow burden of radiologists and further optimize RAI. We also found that radiology trainee involvement during report generation was associated with higher RAI rates, a finding potentially secondary to having a second reader for any given study who may identify additional findings or incidental lesions. Assessing the reasons for the clinical impact of these additional recommendations was outside the scope of our study, and further research is warranted. In our study, increasing radiologist experience was associated with a small (odds ratio, 0.98) but statistically significantly lower RAI rate, which is consistent with prior studies (6,32). However, assessing the clinical implications of such a small change was beyond the scope of our study.

**Table 4: Percentage of RAIs Scored in Each Taxonomy Category in the First 3 Months and Last 3 Months of the Study Period**

| RAI Taxonomy | First 3 Months | Last 3 Months | Odds Ratio* | *P* Value |
|---|---|---|---|---|
| Study site | | | | |
| Actionable | 19 (5.6) | 144 (42.3) | 0.08 (0.04, 0.13) | <.001 |
| Complete | 25 (7.3) | 147 (43.2) | 0.10 (0.06, 0.16) | <.001 |
| Ambiguous | 220 (64.7) | 131 (38.5) | 2.92 (2.14,3.99) | <.001 |
| Conditional | 11 (3.2) | 4 (1.1) | 2.80 (0.88, 8.90) | .11 |
| Alternate | 21 (6.1) | 4 (1.1) | 5.52 (1.87, 16.28) | <.001 |
| Multiplicity | 21 (6.1) | 8 (2.3) | 2.73 (1.19, 6.25) | .02 |
| Control site | | | | |
| Actionable | 51 (15.0) | 47 (13.8) | 1.10 (0.71, 1.68) | .73 |
| Complete | 73 (21.4) | 109 (32.0) | 0.57 (0.41, 0.81) | .001 |
| Ambiguous | 191 (56.1) | 238 (70.0) | 0.54 (0.40, 0.75) | <.001 |
| Conditional | 11 (3.2) | 14 (2.9) | 0.77 (0.34, 1.74) | .68 |
| Alternate | 23 (6.7) | 24 (7.0) | 0.95 (0.52, 1.72) | >.99 |
| Multiplicity | 20 (5.8) | 15 (4.4) | 1.35 (0.68, 2.69) | .48 |

Note.—Unless otherwise indicated, data are numbers of requests for additional imaging (RAIs), and data in parentheses are percentages. *P* values were calculated using a pairwise Fisher exact test between the two time periods for each RAI category.

* Data in parentheses are 95% CIs.

Our study had limitations. First, the interventions were performed at a single institution with a dedicated radiology quality and safety team, a commitment to address potentially unwarranted variations in clinical practice, and an institution-specific electronic closed-loop communication tool. Second, given that the interventions were additive, the final results are best viewed as the cumulative impact of our interventions, rather than being attributed discretely to each single intervention. Further studies are needed to assess whether any single intervention or a subset of interventions described in our study would be effective in optimizing RAI. Third, we analyzed only a random sample of reports to determine rates of actionable RAI and resolution; however, the sample size was statistically determined a priori. Finally, inherent differences in the composition of radiology faculty and institutional culture may have existed between the study and control institutions, which could have limited direct comparisons. However, the purpose of including the concurrent control site was primarily to help confirm the absence of potential confounders in our health care system or the external environment during the study period.

In conclusion, we found that technology-enabled interventions to optimize recommendations for additional imaging (RAIs) in radiology reports may reduce the rates of clinically unnecessary RAIs and improve recommendation clarity and actionability, leading to higher RAI resolution rates. Such changes have the potential to improve patient safety, decrease health care costs, yield fewer diagnostic errors, and reduce low-value imaging follow-up.

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