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SA-CME

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Abstract

Purpose: The aim of this study was to identify organizational factors and quality improvement strategies associated with lower radiation doses from abdominal CT.

Methods: Cross-sectional survey was administered to radiology leaders, along with simultaneous measurement of CT radiation dose among 19 health care organizations with 100 imaging centers throughout the United States, Europe, and Japan, using a common dose management software system. After adjusting for patient age, gender, and size, quality improvement strategies were tested for association with mean abdominal CT radiation dose and the odds of a high-dose examination.

Results: Completed surveys were received from 90 imaging centers (90%), and 182,415 abdominal CT scans were collected during the study period. Radiation doses varied considerably across organizations and centers. Univariate analyses identified eight strategies and systems that were significantly associated with lower average doses or lower frequency of high doses for abdominal CT examinations: tracking patient safety measures, assessing the impact of CT changes, identifying areas for improvement, setting specific goals, organizing improvement teams, tailoring decisions to sites, testing process changes before full implementation, and standardizing workflow. These processes were associated with an 18% to 37% reduction in high-dose examinations ($P < .001$-.03). In multivariate analysis, having a tracking system for patient safety measures, supportive radiology leaders, and obtaining clear images were associated with a 47% reduction in high-dose examinations.

Conclusions: This documentation of the relation between quality improvement strategies and radiation exposure from CT examinations has identified important information for others interested in reducing the radiation exposure of their patients.

Key Words: Organizational innovation, quality improvement, radiation dose, abdominal radiography, x-ray computed tomography

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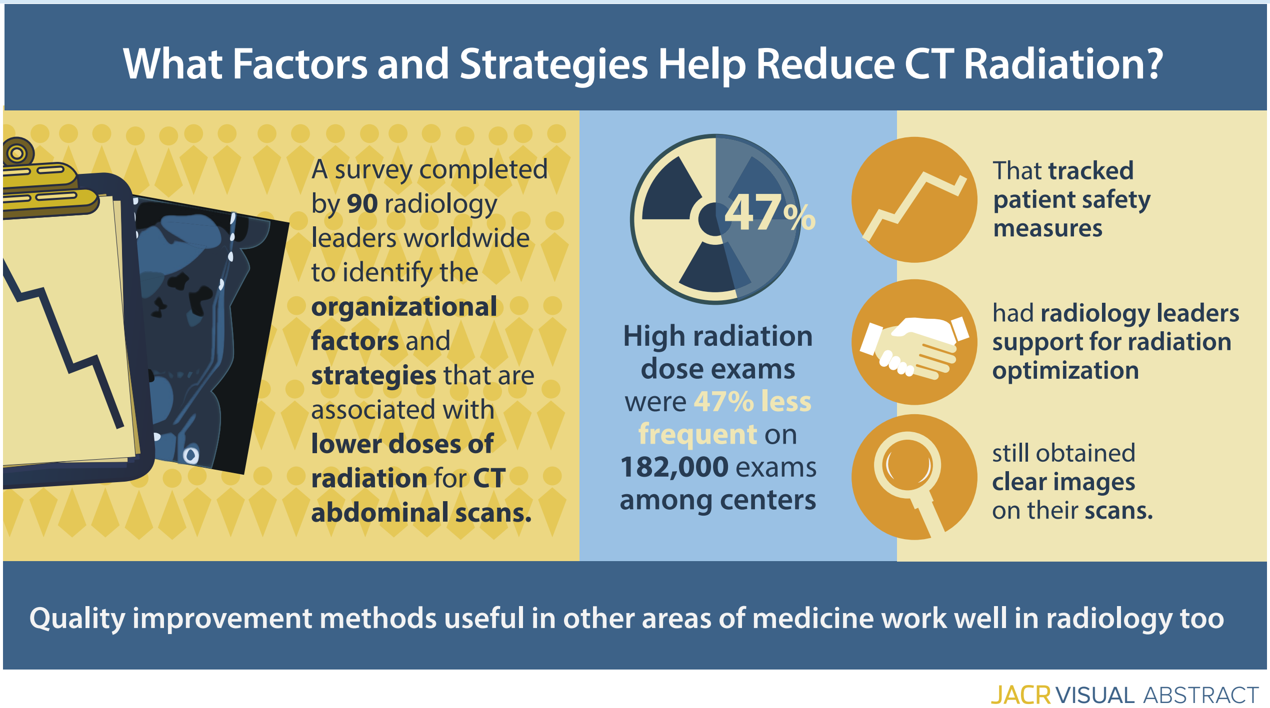
Visual abstract



CT examinations have provided clinicians with substantial improvement in their ability to make diagnoses. However, there is enough concern about overuse that the ACR Foundation convened a summit meeting of 60 organizations in 2009 to identify causes and solutions [1]. Overutilization is a problem for controlling health care costs, but unnecessary examinations also expose patients to high radiation doses, increasing the risk for later development of cancers [2,3]. In one study of nearly 1 million people followed for more than 3 years across the United States, 70% of people underwent at least one radiation-exposing imaging procedure, with 20% receiving at least moderate radiation doses [4]. Importantly, this radiation exposure risk is also subject to wide variation in dose across different procedures and institutions. In a study of 151 organizations across seven countries, abdominal CT examinations had a 4-fold range in mean effective radiation (7.0-25.7 mSv) and a 17-fold range in the proportion of high dose examinations (4%-69%) [5].

Such large variations in performance are widely recognized within the quality improvement field as an opportunity to identify the causes of variation to focus improvement efforts on those causes that are associated with more desirable outcomes [6,7]. Sistrom [8] published a conceptual framework for radiology improvement, and Selby et al [9] showed that even when there is little variation, there may still be a large opportunity for improvement. However, there has been little application of quality improvement methods in radiology, in part because information is lacking about the important contributory factors and effective change strategies for better care.

To explore the relationship between radiation dose and the factors amenable to change, we enrolled 19 diverse radiology organizations with 100 separate imaging sites conducting CT examinations from throughout the United States as well as from Europe and Japan for a trial of different approaches to optimizing radiation doses. The goal of this study is to identify the organizational factors and strategies that were associated with lower radiation exposures for patients in those centers at baseline, before any intervention.

METHODS

Recruitment

Radiology health care organizations that used Radimetrics software (Bayer, Whippany, New Jersey), a radiation dose management tool, were invited by e-mail to participate in the trial. This inclusion criterion provided both an indication that the purchasing organization was interested in managing radiation dose exposures and a consistent means for collecting and measuring radiation doses across organizations in a standardized fashion. Overall, 19 diverse health care systems in 26 US states, England, the Netherlands,

Table 1. Descriptions of participating organizations

Organization, Location	Type of Organization	Affiliated Imaging Centers	Radiologists Who Work at Organization	CT Machines	Abdominal CT Scans
Total		100	1,268-1,298	269	183,415
Center for Diagnostic Imaging in 16 US States	Network of outpatient imaging sites	36	500	61	17,254
Children's Mercy Hospital, Kansas City, Missouri*	Academic hospital	2	2	5	122
City of Hope National Medical Center, Duerte, California	Academic hospital	1	17	3	1,866
Community Healthcare Network, Indianapolis, Indiana	Public hospital	8	50	14	19,254
UT Health East Texas, Tyler, Texas	Academic hospital	7	25	31	14,583
Einstein Medical Center, Philadelphia, Pennsylvania	Academic hospital	4	32	11	6,803
Emory University Hospital, Atlanta, Georgia	Academic hospital	11	160	34	20,807
Huntsville Hospital, Huntsville, Alabama	Academic hospital	5	30-40	13	15,287
Maastricht University Medical Center, Maastricht, the Netherlands	Academic hospital	1	32	5	4,609
Nicklaus Children's Hospital, Miami, Florida*	Academic hospital	1	11	3	116
Mt. Sinai Medical Center, New York, New York	Academic hospital	1	56	9	4,250
Olive View Medical Center, Olive View, California	Academic hospital	1	30	3	6,333
Oxford University Hospitals, Oxford, United Kingdom	Academic hospital	3	66	19	5,446
San Francisco VA Medical Center, San Francisco, California	Academic hospital	1	10	4	1,597
St. Joseph's Hospital, Orange, California	Community hospital	7	90	20	38,072
St. Luke's Hospital, Tokyo, Japan	Academic hospital	3	20-30	9	4,310
University Hospital Essen, Essen, Germany	Academic hospital	4	30	10	5,132
University Hospital of Basel, Basel, Switzerland	Academic hospital	2	50	4	4,061
University of Virginia Hospital, Charlottesville, Virginia	Academic hospital	2	60	11	13,513

*Pediatric hospital: data shown for patients aged $\geq$ 15 years.

Germany, Japan, and Switzerland agreed to participate (see Table 1). Most were academic or teaching systems, but one was a large network of freestanding imaging centers. Out of the total of 19 organizations, 6 included 1 participating center, and the others had 5 to 30 associated imaging centers. The institutional review boards at the University of California, San Francisco (UCSF), and collaborating organizations reviewed and approved the study or relied on the UCSF institutional review board to do so.

Data Collection

Organizational Survey. To collect descriptive information about each organization and imaging center as well as information about their general approach to managing CT services, we developed a short survey that included questions about each center providing CT examinations within that organization. These surveys were to be completed by the organization's principal investigator and a leader at each individual center. The questions asked about the organization's location, structure, services, and patient population. They also asked about CT protocols, the role of medical physicists, and experience with optimizing CT radiation doses. The surveys were distributed electronically via REDCap and sent via e-mail to the principal investigators and site leaders. Follow-up began via e-mail and continued via phone call until we had responses from each participating facility.

Implementation Survey. This survey was designed to identify how CT procedures were implemented within organizations and how each organization addressed the optimization of radiation doses for patients. The survey combined revised versions of two well-established surveys with questions specific to CT dose optimization and was designed to be completed by organizational or site leaders. The four components were as follows:

1. Physician Practice Connection (PPC): This questionnaire was originally created by the National Committee for Quality Assurance to assess implementation of the Chronic Care Model systems in primary care. It has been demonstrated to be reliably completed by a practice leader and to be associated with outcome measures and has been used in many federally funded studies [10-12]. Some wording changes were made to focus on the presence of systematic approaches to managing CT examinations and their associated radiation doses. It contained 14 questions about specific systems, asking whether a particular system is present and works well (1.0 point), present but needs improvement (0.5 points), or absent (0 points) and scored by as the percentage of possible points.
2. Change Process Capability Questionnaire, Part 1 on Practice Readiness (CPCQ1): This questionnaire was originally developed to measure the organizational factors identified by an expert panel as very important to a practice's ability to improve care [13,14]. It has also been used in many federally funded studies for a wide variety of topics. The 23 questions were answered on a 5-point agreement scale and scored to produce a total score as the percentage of possible points available.
3. Change Process Capability Questionnaire, Part 2 on Use of Change Strategies (CPCQ2): Developed in conjunction with CPCQ1 from the recommendations of an expert panel, these 16 questions assessed whether a practice has used each of 16 strategies for improving imaging services. Like the PPC, it has three answer categories for "used and works well," "used but needs improvement," or "no (not used)," and a similar summary score is produced on the basis of the percentage of possible total points achieved
4. Miscellaneous: This component contained 9 questions about the organization's CT protocols, quality improvement experience, and use of the dose measurement software. One question asked about the organization's priority for improving radiation dose in relation to all other priorities. These questions were created to collect specific information and not to produce an overall score.

Survey Process

The survey was distributed electronically via REDCap e-mail. If the survey was not completed, up to three reminders were automatically sent every 8 days. For the purposes of this study, each imaging center was represented by a single survey response. For centers from which we received multiple survey responses, the survey response for inclusion was selected using the following hierarchy: lead radiologist, other radiologist, lead technologist, other technologist, lead medical physicist, other medical physicists, administrator, and other or unknown.

Assessment of Radiation Dose

All analyses were adjusted for patient size, which was estimated using a mean water equivalent diameter of the scanned region. A radiation dose registry was created at UCSF to pool and store data on consecutive CT scans performed at collaborating organizations [5]. Radiation dose data stored in DICOM format at each institution were exported to a local server directly from the CT machines or via the PACS used to review these examinations. Data were stripped of patient-identifying information other than study date and time and transferred to UCSF in real time. Ongoing quality control performed at UCSF ensured that any gap in CT data submission was rapidly corrected and that missing studies were filled in. Any machine that recorded data for less than 10 abdominal CT scans during the study period was removed from the study. The total radiation dose imparted to a patient by the scanner was determined by the dose-length product (DLP). This number can be converted to effective dose, a measure that takes into account the total imparted radiation and the future risk for cancer from this radiation, using a conversion factor of 0.015 for abdominal scans [15].

Analysis

The survey answers were scaled 0 to 1 for analysis. For questions whose available answers range on a 5-point scale (strongly disagree, strongly agree, neutral, agree, and strongly agree), the answers were translated into numeric values of 0 (strongly disagree), 0.25 (disagree), 0.5 (neutral), 0.75 (agree), and 1 (strongly agree). For questions whose answers range on a 3-point scale, the answers were translated into 0 (absent), 0.5 (present but needs improvement), 1 (present and works well). For questions whose answers are true or false, the answers were translated into 0 (false) and 1 (true). For questions whose answers may be given as any number, the responses were rescaled to vary roughly from 0 to 1, where extreme outliers are ignored in the rescaling. Compound scores are computed for questions in the CPCQ1, CPCQ2, and PPC by averaging all given survey responses for each respondent.

The primary outcomes were mean imaging center radiation dose and the imaging center proportion of doses above the 75% at baseline. To study the effect on the mean dose of each survey question, as well as the compound scores of the CPCQ1, CPCQ2, and PPC, we fit log-linear mixed models with the question or compound score of interest as the primary fixed effect and the DLP for each CT scan as the outcome. To study the effect of each survey question on the likelihood of a high-dose study, we created a logistic mixed model in which the outcome was whether the DLP was above 75% at baseline, defined as a DLP of 1,140 mGy · cm (corresponding to an effective dose of 17 mSv). In all models, patient diameter was included as a fixed effect, and the specific machine on which the scan was performed was added as a random effect. For each log-linear model, we computed the expected reduction in mean dose in the population if all respondents strongly agreed. For each logistic model, we computed the expected reduction in the odds of a high-dose examination. For all questions but two, a higher valued (ie, strongly agreeing) survey response would correspond a priori to a decrease in dose. For those two questions, the survey responses were inverted to be consistent in direction.

We fit an additional multivariate log-linear mixed model to find the optimal strategy for lowering dose. This identified the survey answers that in combination were associated with the lowest doses. This was done using a forward selection algorithm whose initial step was a log-linear mixed model with only patient size as a fixed effect and the machine used as a random effect. Additional fixed effects are added in the form of survey question responses, with the metric for inclusion being the expected dose reduction to a patient in the study population if centers changed behavior to strongly agree with all questions in the model. A question was added to the model only if it had a significant impact on dose not accounted for by questions already in the model, and the outcome of interest was the combined impact of all questions added to the model. A question was eligible for inclusion in the multivariate model only if it had a P value of at least .05 in the univariate model and if its addition to the current model would be statistically significant. The forward selection ended when the inclusion of additional questions did not lead to at least an additional 0.5% dose reduction. We fit a multivariate logistic mixed model using the same forward selection algorithm.

RESULTS

Completed implementation survey responses were collected for 90 of 100 imaging centers (90%) and all 19 health care organizations, including survey responses from 5 lead radiologists, 40 nonlead radiologists, 6 lead technologists, 35 nonlead technologists, 3 administrators, and 1 respondent of unknown role. During the study period (November 1, 2015, to October 28, 2016), 183,415 abdominal CT scans and their associated radiation dose measures were assembled from these sites. Table 1 provides a description of each of the 19 organizations. Most organizations identified as academic hospitals, but there was also one that contained a large network of outpatient imaging centers in 16 US states.

Overall the mean radiation dose for abdominal CT was 788 ± 588 mGy · cm (interquartile range, 384-1,040 mGy · cm). This corresponds to an average effective dose of 12.7 ± 9.7 mSv (interquartile range, 6.26-16.3 mSv). The imaging center mean DLP varied from 355 to 1,826 mGy · cm when all patients are standardized to be of median abdominal circumference. Overall the proportion of high-dose examinations was 22.1%, and the imaging center proportion of high-dose examinations varied from 2.1% to 78.9%.

The organizations with the lowest mean doses were either children's hospitals or European, both of which are known to be more sensitive to radiation concerns. In univariate analyses (see Table 2), the summary scores on the implementation survey for both practice readiness and use of change strategies showed a significant relationship to the frequency of high-dose examinations (reductions of 39% and 32%, respectively, if all facilities were to strongly agree with all questions in these sections) but not to average dose. There were 14 individual questions that were significantly associated with radiation doses.

Imaging centers that track any patient safety measures, that assess the impact of any CT changes that are made, that set specific goals for improving radiation dose, that organize teams to improve doses, that pilot-test process changes before full implementation, and that standardize workflow to encourage dose optimization were associated with at least 30% reduction in high-dose examinations in comparison with organizations that did not report these activities. Furthermore, radiation leaders who support dose optimization and organizations with leadership enthusiastic about dose optimization had at least 20% fewer high-dose examinations.

It also shows that both the total number of radiology protocols and the number of active quality improvement projects that are focused on optimizing radiation dose are significantly associated with both average dose and the frequency of high-dose examinations. Interestingly, the attitudes of radiologists (and radiologic technologists), limited resources, and organizational stress were not related to either

Table 2. Survey questions that are significantly related to radiation dose in univariate analysis, the mean score for each question, the percentage of imaging centers whose respondents strongly agreed or disagreed with the statement, and the percentage reduction in average dose and probability of high-dose examinations if all facilities strongly agreed with the question

Survey Questions[‡]	Mean Score	Percentage of Respondents Who: Agree[§]	Disagree[‖]	Average Dose*: % Reduction	P	High Dose[†]: % Reduction	P
Practice systems				0.3	0.96	17	0.34
We track patient safety measures (nonradiology)	.55	36	47	10	.01	32	<.001
Practice readiness				8	.17	39	.016
1. We assess the impact of CT changes made	.73	71	8			31	.01
2. Radiology leaders support dose optimization activities	.83	87	2	7	<.001	27	<.001
3. We lowered CT dose in past year	.83	85	3	7	.01	25	<.001
4. We review processes and identify areas for improvement	.75	71	8	3	0.27	18	.03
5. Leaders of optimization are enthusiastic	.69	72	2	5	0.13	23	.03
Change strategies				7	.11	32	.03
1. We set specific goals for improving radiation dose and image quality	.55	32	24	8	.04	37	<.001
2. We organize a team to improve CT dose	.51	33	31	8	.01	33	<.001
3. We tailor decisions to site needs	.66	44	15	8	.04	31	.02
4. We pilot-test process changes before implementation	.58	37	23	8	.04	30	.03
5. We standardized workflows to encourage dose optimization	.83	65	1	5	.03	31	.01
Miscellaneous							
1. Number of protocols	15	—	—	19	.01	38	<.001
2. Number of active QI projects on radiation dose	2	—	—	6	.01	22	.01
3. We obtain clear images of abdominal CT	.92	92	9	2	<.001	8	<.001

Note: QI = quality improvement.
*Percent reduction in expected dose length product if all facilities strongly agreed.
[†]Percent reduction in probability of high dose exams (from baseline 25%) if all facilities strongly agreed.
[‡]Abbreviated versions of the questions.
[§]Includes responses of "yes, and works well" or combined responses of "agree" and "strongly agree," depending on question.
[‖]Includes responses of "no" or combined responses of "disagree" and "strongly disagree," depending on question.

Table 3. Multivariate analysis of statements that are significantly related to radiation dose

Model	Source	Statement	Reduction in Dose if All Facilities Strongly Agreed: % (95% CI)
Average dose	Practice systems	We track patient safety measures (nonradiology)	
	Change capability	Radiology leaders support dose optimization activities	12 (11.8-13.1)
	Miscellaneous	We obtain clear images of abdominal CT	
High dose	Practice systems	We track patient safety measures (nonradiology)	
	Change capability	Radiology leaders support dose optimization activities	47 (44.5-49.6)
	Miscellaneous	We obtain clear images of abdominal CT	

Note: CI = confidence interval.

mean dose or the likelihood of high radiation dose. There was no significant relationship between an organization's priority for optimizing dose and mean dose.

The multivariate analysis showed that three survey questions informed both mean dose and high-dose reduction (see Table 3). This suggests that if all imaging centers reported tracking nonradiation measures of patient safety, had radiology leaders who supported dose optimization activities, and had clear images of abdominal CT examinations (meaning that the lower doses did not come at the expense of imaging quality), the average radiation dose would decrease by 12%, and the probability of high-dose examinations would decrease by 47%.

DISCUSSION

In summary, this cross-sectional analysis of the relation between CT radiation exposure and various organizational activities and behaviors identified a number of factors strongly associated with both average and high radiation dose. Most important, the tracking of patient safety measures and having radiology leadership who support dose optimization were associated with nearly a 50% reduction in high-dose examinations. All of the identified factors can be modified, and radiology organizations and imaging centers should consider these if they are interested in optimizing the radiation doses for their patients.

The most important factor (associated with both lower average dose and fewer high-dose examinations) is having support from radiology leaders for dose optimization activities. Virtually every study of quality in any type of organization has found that is the critical foundation for better quality. However, it is less clear why tracking patient safety measures and having clear images were part of the multivariate package. We suspect that these two factors are simply markers for broader aspects of achieving radiation safety goals. Tracking other safety measures was one of the least frequent activities, so it may mean that organizations doing so have taken an unusually broad approach to improving quality. On the other hand, it is likely that even strong leadership support will not be effective if it pushes dose levels so low that radiologists can no longer be confident of their readings for images that are not sharp.

Several of the factors identified in the univariate analysis did not make it through the multivariate analysis, but this does not mean that they were not important but rather that they may have simply been markers for other unmeasured factors. These practices provide supportive evidence that the systematic approach to quality improvement used in other settings will probably also be effective for dose optimization in imaging centers. It is hard to imagine a serious quality improvement effort in any industry that would not start by identifying processes for improvement, setting specific goals, organizing a multidisciplinary team, combining standardization with tailoring change to site needs, pilot testing before implementation, and then assessing the impact of the changes made, all strategies that were identified as important in the univariate analysis.

Finally, it may also be helpful to know that imaging centers are able to achieve dose optimization regardless of radiologist or other staff member attitudes and despite limited resources and organizational stress, none of which were associated with either average dose or frequency of high-dose examinations.

These findings may not be surprising to those experienced in quality improvement, but because most quality improvement initiatives in medicine have focused on primary care or inpatient services, it is helpful to have them confirmed in a new field. It may also be helpful to be aware that change in performance measures in other medical fields is generally slow, despite exhortation from enthusiastic leaders who want to change long-established traditions and care processes overnight. Our studies of change in performance over time in many primary care clinics as they become patient-centered medical homes have demonstrated the need for prolonged efforts and awareness that the rate of change will be slow, even when health care systems are exerting large efforts to improve [16,17].

Limitations

The principal limitation of this study is the cross-sectional nature of the data. However, many of these organizations had been working on dose optimization for some time before this study, which was one of the reasons for their interest in participating. Thus, we can only say that at the time of the surveys, certain activities and factors were associated with lower doses. More definitive relationships will require analysis of changes over time. We are also relying on self-report from a single leader at each site, who may have a limited understanding of some of the factors addressed, and this does not represent documentation of actual practice. However, in the original survey's validation studies, self-report correlated fairly well with an independent audit [10]. Finally, these participating organizations are probably not representative of all imaging providers, in being larger and more interested in addressing this topic (as indicated by their purchase of Radimetrics software and agreeing to participate in this study).

It is important to note that the primary outcomes of interest in this study are the expected impacts of survey questions on population dose, not individual dose. That is, our outcomes do not seek to compare a theoretical imaging center that disagrees with survey questions with a theoretical imaging center that agrees with survey questions but rather illustrate the opportunity available in the population of imaging centers for improvement if they all changed from their current behaviors to strongly agree with survey questions. Under this paradigm, a survey question that is highly associated with dose levels, but that most imaging centers already agree with, would be considered "low impact," in that there are few opportunities for the population to improve. On the other hand, a survey question that has comparatively modest association with dose, but whose responses vary greatly across imaging centers, presents a high opportunity for the population to improve and is thus "high impact." These findings are consistent with what has been demonstrated in other settings and fields and topics, so they should be helpful to those interested in addressing the topic of dose optimization in radiology. In particular, they highlight again that improvement in radiation doses from CT examinations requires a conscious, organized effort to improve the processes and systems used to deliver those services. Improvement will not come from efforts to change the attitudes, knowledge, and behaviors of individual health care personnel, even though some attention to those factors may be needed to facilitate the uptake and use of more systematic changes.

TAKE-HOME POINTS

- There is wide variation in radiation doses from the same CT examinations among leading radiology organizations.
- Fourteen different changeable factors were significantly associated with lower radiation doses.
- Statistically speaking, if all imaging centers in this study tracked nonradiation measures of patient safety, had radiology leaders who supported dose optimization activities, and had clear images, the average dose would decrease by 12%, and the probability of high-dose examinations would decrease by 47%.

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