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An Image Quality–informed Framework for CT Characterization

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See also the editorial by Mahesh in this issue.

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Background: Lack of standardization in CT protocol choice contributes to radiation dose variation.

Purpose: To create a framework to assess radiation doses within broad CT categories defined according to body region and clinical imaging indication and to cluster indications according to the dose required for sufficient image quality.

Materials and Methods: This was a retrospective study using Digital Imaging and Communications in Medicine metadata. CT examinations in adults from January 1, 2016 to December 31, 2019 from the University of California San Francisco International CT Dose Registry were grouped into 19 categories according to body region and required radiation dose levels. Five body regions had a single dose range (ie, extremities, neck, thoracolumbar spine, combined chest and abdomen, and combined thoracolumbar spine). Five additional regions were subdivided according to dose. Head, chest, cardiac, and abdomen each had low, routine, and high dose categories; combined head and neck had routine and high dose categories. For each category, the median and 75th percentile (ie, diagnostic reference level [DRL]) were determined for dose-length product, and the variation in dose within categories versus across categories was calculated and compared using an analysis of variance. Relative median and DRL (95% CI) doses comparing high dose versus low dose categories were calculated.

Results: Among 4.5 million examinations, the median and DRL doses varied approximately 10 times between categories compared with between indications within categories. For head, chest, abdomen, and cardiac (3 266 546 examinations [72%]), the relative median doses were higher in examinations assigned to the high dose categories than in examinations assigned to the low dose categories, suggesting the assignment of indications to the broad categories is valid (head, 3.4-fold higher [95% CI: 3.4, 3.5]; chest, 9.6 [95% CI: 9.3, 10.0]; abdomen, 2.4 [95% CI: 2.4, 2.5]; and cardiac, 18.1 [95% CI: 17.7, 18.6]). Results were similar for DRL doses (all $P < .001$).

Conclusion: Broad categories based on image quality requirements are a suitable framework for simplifying radiation dose assessment, according to expected variation between and within categories.

Radiation doses for CT are highly variable across patients and institutions (1). Although some of this variation reflects hardware characteristics and appropriate differences because of patient factors such as size and clinical indication for imaging, most of the variation stems from provider choices in how CT is performed (2). The protocols used in CT are not standardized according to clinical indications across locations or even among providers within the same location. Thus, protocol decisions affect considerably the amount of radiation patients receive during CT scanning (2,3). Radiologists, medical physicists, and professional organizations have made considerable efforts to standardize protocols (4–8), yet large variations in radiation dose persist (2,9).

Excessive radiation from undergoing multiple or higher-dose CT examinations may be associated with increased cancer risk (10,11); thus, reducing radiation whenever possible is beneficial to the patient. Because the amount of radiation needed for adequate image quality varies according to anatomic region and clinical indication, what constitutes an excessive radiation dose will also vary according to anatomic region and clinical indication.

Abbreviations

$CTDI_{vol}$ = volume CT dose index, DLP = dose-length product, DRL = diagnostic reference level

Summary

A framework that assigns CT examinations into broad categories based on body region and image quality requirements simplifies assessment of radiation dose for benchmarking and for developing CT protocols.

Key Results

- Based on 4.5 million CT examinations grouped into 19 categories according to body region and expected image quality requirements, radiation doses varied approximately 10 times between categories compared with between indications within categories ($P < .001$), meaning the categories are valid.
- Radiation doses were significantly higher for examinations assigned to the high versus low radiation dose category; for example, 3.4-fold higher for head; 9.6 for chest; 18.1 for cardiac; and 2.4 for abdomen.
- Approximately 91% (4 129 165 examinations) of diagnostic CT examinations can be assigned to one of the 19 categories; three categories—routine head, routine chest, and routine abdomen—account for 67% (2 796 365 examinations) of total examinations.

One approach to aid in the selection and assessment of CT radiation doses is the publication of benchmarks that clinicians can use when making local choices for how to scan patients. The most commonly used benchmarks are created according to protocol, such as single-phase and multiple-phase abdomen CT (1). The primary challenge in using a protocol-based approach for setting benchmarks is that there is little consensus or consistency in how patients are assigned to protocol. Therefore, assessing radiation doses at a facility using only information from protocols can lead to misleading results, as protocol choice is at the discretion of the radiologist and is a key determinant of quality. Stratifying according to that choice eliminates the ability to form a judgment about this important component of quality. Furthermore, imaging facilities often create customized sets of protocols, and the idiosyncratic nature of such protocols makes comparisons difficult across sites.

To simplify evaluation of radiation doses, we developed a framework that assigns CT examinations into 19 broad categories based on body region and clinical indication, where we grouped indications that have similar image quality requirements into the same category. These 19 categories capture the vast majority of reasons why patients undergo CT, and the use of these categories can aid in benchmarking. We used data from a large CT registry to assess the content validity of our approach by examining actual radiation doses within and across categories.

Materials and Methods

Registry and Collaborating Institutions

The University of California San Francisco International CT Dose Registry includes CT examination data captured from 161 hospitals or imaging facilities across seven countries. The registry is smaller than, but broadly similar to, the larger American College of Radiology Dose Index Registry (12). Although both registries focus on dose optimization, a defining purpose of the University of California San Francisco registry has been to assess radiation dose delivered across a global range of facilities and to use these data to develop and study the impact of interventions to improve the safety of CT. The data are captured in a manner compliant with the Health Insurance Portability and Accountability Act using dose management software (Radimetrics, Bayer) and have been used previously to describe factors associated with radiation dose levels, in the context of a randomized controlled trial (2,13). The institutional review boards at the lead and collaborating institutions approved the study, relied on the lead institution's approval, or considered the study exempt human subjects research.

Study Population

Drawing from the registry, we retrospectively analyzed consecutive diagnostic CT examinations performed from January 1, 2016, to December 31, 2019, in patients aged 18 years and older. Data were derived from 383 scanners, including 74 models from the four largest manufacturers—GE Healthcare, Philips, Siemens, and Canon Medical Systems.

Image Quality–informed Framework for CT Categories

Because different parts of the body require different amounts of radiation to create images sufficient for diagnosis, the framework first relies on categorizing CT examinations into 10 body regions. In five of these regions (ie, extremities, neck [which includes cervical spine], thoracolumbar spine [reflecting either thoracic spine or lumbar spine], combined chest and abdomen, and combined thoracolumbar spine [reflecting both thoracic and lumber spine]), clinical indications for scanning do not play a substantial role in altering the amount of radiation needed; thus, there is a single category for each of these body regions. In five other body regions (ie, head, chest, cardiac, abdomen, and combined head and neck), clinical indications affect the optimal radiation dose to achieve differing image quality requirements, and CT examinations were divided based on clinical indications into stand-alone low, routine, or high dose categories (Table 1). The approach to determining low, routine, or high radiation doses within these categories was informed by the following: *(a)* a review of the published literature; *(b)* consultation with radiologists with specialty expertise; *(c)* input from a technical expert panel assembled in relation to the creation of a CT quality measure for the Centers for Medicare and Medicaid Services; and *(d)* empirical evaluation of 4.5 million consecutive CT examinations, described herein (14).

We constructed the CT categories based on perceived image quality requirements, which have face validity as assessed by the technical expert panel (14). For example, the image quality required to observe a small, well-defined structure such as a lung nodule surrounded by air is less than the quality needed to study the margins of a mass adjacent to other organs when assessing the extent of a lung cancer. Thus, these indications are included in different CT categories—low dose chest and routine dose chest, respectively. There were no direct image quality assessments made as part of this research.

The emphasis in creating the CT categories was to identify indications that were exceptions to the routine dose

Table 1: Indications Associated with Low, Routine, and High Radiation Dose CT Categories for Head, Chest, Cardiac, and Abdomen Imaging

Radiation Dose Level	Indications for Head Imaging	Indications for Chest Imaging	Indications for Cardiac Imaging	Indications for Abdomen Imaging
Low dose	Facial skeleton; sinus; bone; ventricular shunt	Lung cancer screening; lung nodule surveillance	Coronary calcium scoring	Colon cancer screening; renal stones (known or suspected); bladder (without contrast material)
Routine dose	Suspected hemorrhage (stroke); trauma	Angiography; cancer;* interstitial lung disease; pulmonary embolism; trauma; high resolution	Angiography, coronary	Abscess; angiography; gastrointestinal tract evaluation, enterography;† liver (not otherwise specified); trauma
High dose	Perfusion angiography	Dissection	Transcatheter aortic valve replacement	Abdominal run-off; acute gastrointestinal bleeding; adrenal nodule; angiography for aortic injury;‡ biliary cancer; bladder cystography (with contrast material); fistula; hepatocellular cancer; metastatic cancer;§ pancreas (pancreatic cancer); renal mass (hematuria or cancer); transplant (donor, recipient, or postoperative); urography

Note.—These listed diagnoses are usually suspected, not confirmed, at the time of imaging.

* Cancer includes evaluation for suspected cancer, staging of known cancer, and evaluation for suspected metastatic disease.

† Gastrointestinal tract symptoms include abdominal pain, weight loss, nausea, vomiting, and diarrhea.

‡ Angiography for aortic injury includes assessment for rupture, dissection, and endovascular leak.

§ High radiation dose for abdomen imaging includes evaluation for suspected cancer symptoms, cancer staging, and evaluation for metastatic disease in the liver, pancreas, biliary system, peritoneum, breast, kidney, adrenal gland, bladder, or unknown primary tumor.

category, rather than to identify every indication for scanning within the routine category. For example, imaging of facial bones for a suspected fracture would require a lower radiation dose, whereas imaging of brain tissue to assess perfusion related to a suspected stroke would require a higher radiation dose, compared with the routine dose head category. The requirement for multiphase scanning was an important consideration for assigning indications to high dose categories. Combining the five categories with a single radiation dose range, the four regions subcategorized as low, routine, or high dose, and the routine and high dose for combined head and neck categories resulted in 19 total categories. The body region and clinical indication for each CT examination in the registry was determined using natural language processing applied to text strings in the Digital Imaging and Communications in Medicine metadata, including the study description and protocol name.

The method of using the Digital Imaging and Communications in Medicine metadata to assign CT examinations to the 19 CT categories was validated by comparing this approach to a determination based on a detailed chart review. Full medical records, including physician notes, laboratory and pathologic results, and ordering indication, were abstracted by a radiology technologist to create the reference standard CT category assignment for a randomly selected sample of 1102 patients who underwent CT at a single health system. The CT category derived from Digital Imaging and Communications in Medicine metadata was correct for 911 of the 1012 scans (90%).

Radiation Dose

CT scanners report radiation dose metrics derived from acquisition parameters that correlate closely with absorbed dose and imparted energy, and from which these variables can be estimated. These scanner-reported metrics are herein referred to as "radiation dose." The radiation dose for each CT examination includes all irradiating events that were part of that examination. Two radiation dose metrics are reported—volume CT dose index ($CTDI_{vol}$) in milligray and dose-length product (DLP) in milligray-centimeter. DLP values were summed across all irradiating events to generate scanning-level DLP, and $CTDI_{vol}$ was a mean weighted according to scanning length. All analyses are adjusted for patient size using the midscanning water-equivalent diameter (15). The analyses did not adjust for phantom, as CT examinations in the registry had virtual uniformity in phantom selection by body region. The diagnostic reference level (DRL) was defined as the 75th percentile of the observed distribution of size-adjusted $CTDI_{vol}$ and DLP.

Statistical Analysis

For each CT category, the scanning frequency and the median and DRL in radiation dose for $CTDI_{vol}$ and DLP were calculated. For the head, chest, cardiac, and abdomen categories, we compared mean doses between low and high dose categories using analysis of variance and estimated ratios of the median radiation doses, with 95% CIs, after adjusting for patient size. $P < .05$ was considered a statistically significant difference.

For each indication within the head, chest, abdomen, and cardiac low, routine, and high dose categories, the $CTDI_{vol}$ versus DLP was graphed showing 25th, 50th, and 75th percentiles. Two sets of analysis of variance analyses were conducted with size-adjusted DLP as the outcome variable. Analysis of variance uses *F* tests to statistically test the equality of means. The *F* statistic is a ratio of two variances (ie, a measure of dispersion). First, we assessed whether the radiation dose varied according to clinical indications within each category. A finding that radiation doses were strongly associated with clinical indications within a category would suggest that the determination of indication for each examination was accurate. Second, we compared the variation in radiation doses within a category (eg, low dose head) with the variation in doses across categories within the same body region (eg, low, routine, and high dose head). A finding of greater variation across categories within a body region than that within the categories of that body region would suggest the assignment of clinical indications to the low, routine, or high dose category is appropriate. R software (version 3.6.3, R Foundation for Statistical Computing) was used for all analyses.

Results

Approximately 4.5 million CT examinations were included (Table 2). Overall, 80.9% of the examinations (3 671 128) were from the United States. The 19 categories capture approximately 91.0% of CT examinations (4 129 165) in the registry during the testing period. The number of CT examinations performed for each age group increased with age up to 70 years. The body regions of head, chest, and abdomen comprised 71.9% (3 266 546) of total CT examinations. Within these three body regions, the routine category accounted for 67% of examinations (2 796 365) (83.4% of head examinations [1 040 518], 94.8% of chest examinations [753 583], and 86.2% of abdominal examinations [1 002 264]). As a result, around six in 10 CT examinations were in the categories of routine dose abdomen, routine dose head, or routine dose chest (Table 3). The median and DRL for DLP and $CTDI_{vol}$ were significantly different across the 19 categories ($P < .001$ for all analysis of variance values).

DLP Findings

Next, we assessed the DLP and $CTDI_{vol}$ to determine whether there were differences in radiation doses across different CT categories. Within the head, chest, abdomen, and cardiac body regions, the median and DRL radiation doses for DLP were significantly different across the low, routine, and high dose categories ($P < .001$ for all) (Table 3, Fig 1). For

Table 2: Characteristics of Included Patients and CT Examinations

Characteristic	No. of CT Examinations (n = 4 537 341)
Time period	
January 1, 2016–December 31, 2016	1 265 334 (27.9)
January 1, 2017–December 31, 2017	1 259 131 (27.8)
January 1, 2018–December 31, 2018	1 131 946 (24.9)
January 1, 2019–December 31, 2019	853 398 (18.8)
Missing	27 532 (0.6)
Country	
Germany	112 956 (2.5)
Israel	318 293 (7.0)
Japan	92 845 (2.0)
Netherlands	88 321 (1.9)
Switzerland	116 594 (2.6)
United Kingdom	109 672 (2.4)
United States	3 671 128 (80.9)
Missing	27 532 (0.6)
Age (y)	
18–29	351 104 (7.8)
30–39	385 733 (8.6)
40–49	527 455 (11.7)
50–59	806 853 (17.9)
60–69	956 631 (21.2)
70–79	802 601 (17.8)
80–89	476 108 (10.6)
90 and older	203 324 (4.5)
Missing	35 989 (0.8)
Sex	
F	2 316 913 (51.4)
M	2 152 643 (47.9)
Other	29 140 (0.6)
Unknown	2656 (<0.1)
Missing	27 532 (0.6)
Scanner manufacturer	
Canon	414 408 (9.1)
General Electric	1 900 558 (41.9)
Philips	874 142 (19.3)
Siemens	1 294 716 (28.5)
Missing	53 517 (1.2)
Body region	
Head	1 243 712 (27.4)
Neck	262 037 (5.8)
Chest	798 780 (17.6)
Cardiac	60 381 (1.3)
Abdomen	1 163 673 (25.6)
Thoracolumbar spine	141 043 (3.1)
Extremity	96 548 (2.1)
Combined chest and abdomen	260 090 (5.7)
Combined head and neck	98 184 (2.2)
Combined thoracolumbar spine	4717 (0.1)
Missing, unidentified, or other combined body regions	408 176 (9.0)

Note.—Data are numbers of examinations, with percentages in parentheses.

Table 3: Frequency of CT Categories and 50th and 75th Percentiles in DLP and $CTDI_{vol}$ Values of Radiation Dose for Each Category

Location and Dose	No. of Examinations	50th Percentile in Radiation Dose for DLP		75th Percentile in Radiation Dose for DLP		50th Percentile in Radiation Dose for $CTDI_{vol}$		75th Percentile in Radiation Dose for $CTDI_{vol}$	
		Dose (mGy · cm)	Relative Dose*	Dose (mGy · cm)	Relative Dose*	Dose (mGy · cm)	Relative Dose*	Dose (mGy · cm)	Relative Dose*
Head									
Low dose	143 093 (3.5)	375	NA	622	NA	20	NA	31	NA
Routine dose	1 040 518 (25.2)	852	NA	1050	NA	45	NA	55	NA
High dose	60 101 (1.5)	1280	3.4 (3.4, 3.5)	1866	3.0 (3.0, 3.0)	94	4.8 (4.8, 4.87)	150	4.8 (4.7, 4.8)
Chest									
Low dose	43 202 (1.0)	85	NA	111	NA	2	NA	3	NA
Routine dose	753 583 (18.3)	347	NA	556	NA	9	NA	13	NA
High dose	1995 (>0.1)	813	9.6 (9.3, 10.0)	1243	11.2 (10.8, 11.7)	12	4.9 (4.7, 5.1)	17	5.5 (5.3, 5.6)
Abdomen									
Low dose	77 464 (1.9)	508	NA	768		9	NA	14	NA
Routine dose	1 002 264 (24.3)	657	NA	1063	NA	11	NA	17	NA
High dose	83 945 (2.0)	1237	2.4 (2.4, 2.5)	1926	2.5 (2.5, 2.5)	10	1.1 (1.1, 1.2)	15	1.1 (1.1, 1.1)
Cardiac									
Low dose	17 164 (0.4)	82	NA	112	NA	6	NA	7	NA
Routine dose	39 031 (0.9)	350	NA	743	NA	11	NA	23	NA
High dose	4186 (0.1)	1481	18.1 (17.7, 18.6)	2217	19.8 (19.1, 20.4)	24	4.0 (3.8, 4.2)	54	6.2 (6.1, 6.3)
Location									
Neck	262 037 (6.3)	409	NA	612	NA	16	NA	21	NA
Thoracolumbar spine	141 043 (3.4)	753	NA	1055	NA	21	NA	30	NA
Extremity	96 548 (2.3)	299	NA	588	NA	10	NA	18	NA
Combination									
Chest and abdomen	260 090 (6.3)	768	NA	1261	NA	10	NA	15	NA
Head and neck routine	88,106 (2.1)	957	NA	1309	NA	21	NA	32	NA
Head and neck high	10 078 (0.2)	2547	NA	3646	NA	145	NA	25	NA
Thoracolumbar spine	4717 (0.1)	807	NA	1234	NA	16	NA	20	NA

Note.—Except where indicated, data are numbers of examinations, with percentages in parentheses. $P < .001$ for all. For head, chest, abdomen, and cardiac, relative radiation dose and 95% CIs for the high dose versus low dose category are provided. Fiftieth percentile is the median, and 75th percentile is the diagnostic reference level. Examinations with unknown CT categories (ie, missing, unidentified, or other combined body regions) were not included in this Table. $CTDI_{vol}$ = volume CT dose index, DLP = dose-length product, NA = not applicable.

* Numbers in parentheses are 95% CIs.

example, for head, the median DLP was 375 mGy · cm for low dose, 852 mGy · cm for routine dose, and 1280 mGy · cm for high dose (difference between categories, $P < .001$). Within these body regions, the relative radiation doses between the high dose versus low dose categories were significantly different, which suggests the assignment of the indications to the low, routine, and high dose categories was appropriate, thus validating the categories. For median DLP, these ratios were 3.4 (95% CI: 3.4, 3.5) for head; 9.6 (95% CI: 9.3, 10.0) for chest; 2.4 (95% CI: 2.4, 2.5) for abdomen; and 18.1 (95% CI: 17.7, 18.6) for cardiac (all $P < .001$). For DRL DLP, these ratios were similar. Taken together, the finding of large differences in radiation doses across the different categories suggests that the assignment of specific clinical indications to each category is appropriate.

$CTDI_{vol}$ Findings

As with DLP, the median and DRL $CTDI_{vol}$ were higher within each body region for the high dose compared with the low dose categories (Table 3, Fig 1). For example, for head CT, the median $CTDI_{vol}$ was 20 mGy for low dose, 45 mGy for routine dose, and 94 mGy for high dose (difference between categories, $P < .001$). The ratio of median radiation doses using $CTDI_{vol}$ was 4.8 (95% CI: 4.8, 4.8) for head; 4.9 (95% CI: 4.7, 5.1) for

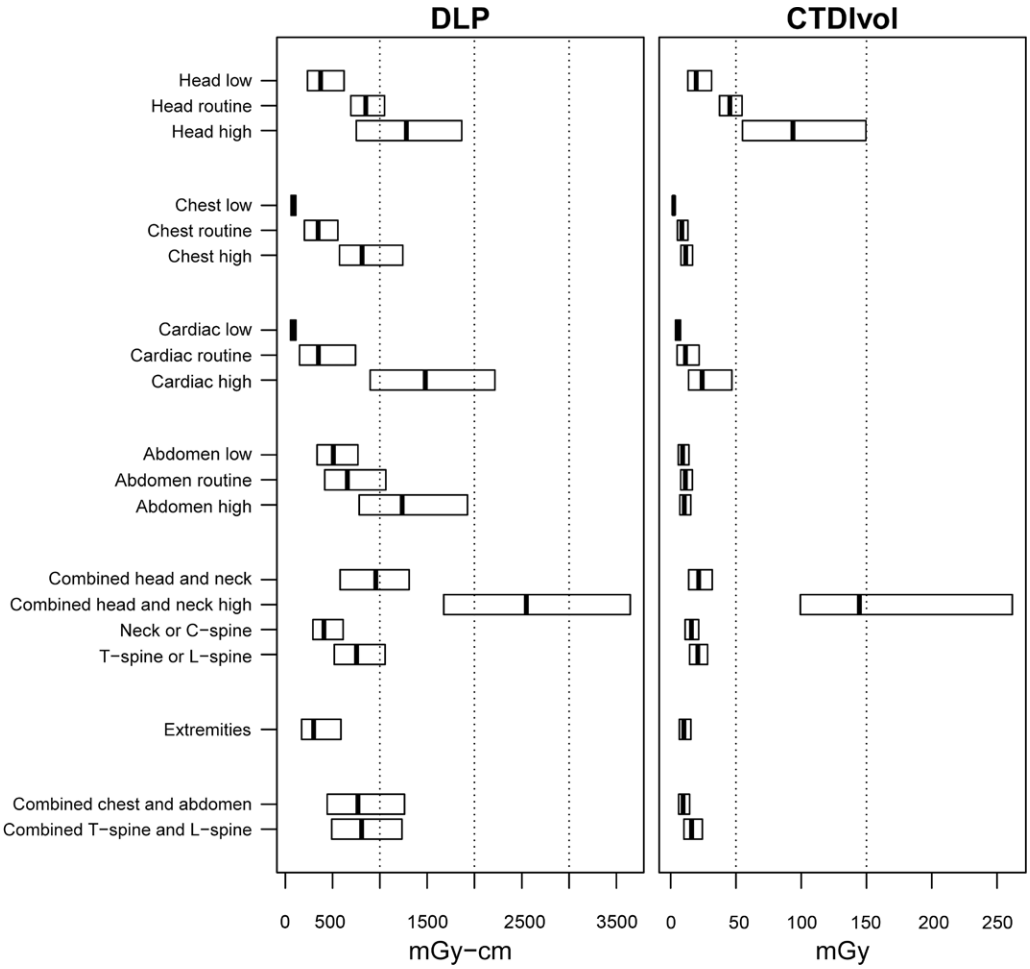

Figure 1: Box plots show distribution of dose-length product (DLP) and volume CT dose index ($CTDI_{vol}$) for each CT category. Box edges indicate 25th and 75th percentiles. Thick vertical line indicates median. C = cervical, L = lumbar, T = thoracic.

chest; 1.1 (95% CI: 1.1, 1.2) for abdomen; and 4.0 (95% CI: 3.8, 4.2) for cardiac.

Clinical Indications

$CTDI_{vol}$ and DLP associated with specific indications that contributed to the head, chest, abdomen, and cardiac CT categories are shown in Table 4, and the $CTDI_{vol}$ and DLP of each indication are shown in Figure 2. Head, chest, and cardiac imaging had relatively clear separation in DLP across the subcategories (Fig 2). Abdominal imaging showed more overlap between subcategories. Taken together, although these four body regions exhibit variation in radiation doses based on clinical indications within each CT category (Tables 4, 5), the variation was far greater between CT categories than within categories (Figure 2).

Discussion

We described a framework to assign diagnostic CT examinations into broad categories based on a combination of body region and clinical indications. The distribution of study types, in particular those of the head, chest, and abdomen, is similar to the recent U.S. National Council on Radiation Protection and Measurements Report 184 (12). Within the head, chest, abdomen, and cardiac body regions, the median and diagnostic reference level radiation doses for volume CT dose index ($CTDI_{vol}$) and dose-length product (DLP) were significantly different across the low, routine, and high dose categories. The larger differences in $CTDI_{vol}$ and DLP between categories in comparison to within categories validates the 19 categories. The proposed 19 categories offer a simplified and valid alternative for assessing radiation dose in comparison to protocol-specific benchmarking widely in use (1). The finding of large differences in both $CTDI_{vol}$ and DLP across the different categories suggests that the assignment of specific clinical indications to each category is appropriate. We found larger differences between categories within body regions using DLP than in those using $CTDI_{vol}$. This was expected, as the indications were categorized according to the total expected radiation dose and not according to the average dose per rotation. For many high dose categories, the higher dose is the result of multiphase scanning rather than a higher dose per rotation.

The purpose of this framework is not to provide benchmark doses according to indication or category, but it may yield guidance for standardizing protocols, assigning patients to the appropriate protocol, and assessing whether a facility's radiation doses are appropriate relative to image quality requirements. Three categories—routine dose head (1 040 518 examinations), routine

Table 4: Median, 25th, and 75th Percentiles of DLP and $CTDI_{vol}$ for Each Clinical Indication for Head, Chest, Cardiac, Abdomen, and Combined Head and Neck Body Regions

CT Category and Indication	No. of Examinations	$CTDI_{vol}$*	DLP*
Head			
Low dose			
Sinus	55 190	17 (11–22)	262 (167–383)
Temporal bone	13 628	38 (29–55)	417 (293–595)
Ventricular shunt	30	18 (18–18)	386 (368–408)
Facial skeleton	74 245	21 (14–32)	531 (310–716)
Routine dose			
Stroke	23 026	46 (42–53)	891 (778–1066)
Head, routine or not otherwise specified	970 080	45 (37–55)	851 (688–1048)
Trauma	47 412	45 (40–52)	851 (761–1085)
High dose			
Perfusion angiography	60 101	94 (55–150)	1280 (751–1866)
Chest			
Low dose			
Lung cancer screening and nodule surveillance	43 202	2 (2–3)	85 (62–111)
Routine dose			
Chest, routine or not otherwise specified	492 726	8 (5–12)	303 (176–504)
Pulmonary embolism	93 648	10 (6–15)	373 (236–565)
High resolution	26 718	9 (6–13)	428 (292–601)
Angiography	126 363	11 (8–16)	441 (293–712)
Interstitial lung disease	2690	7 (4–9)	545 (318–759)
Trauma	9726	15 (10–0)	657 (474–980)
Lung cancer	1712	2 (2–7)	69 (55–336)
High dose			
Dissection	1995	12 (8–17)	813 (574–1243)
Cardiac			
Low dose			
Coronary calcification	17 164	6 (4–8)	82 (56–112)
Routine dose			
Cardiac, routine, or not otherwise specified	12 125	7 (3–16)	220 (74–499)
Coronary angiography	26 906	13 (7–25)	417 (191, 903)
High dose			
Transaortic valvular replacement	4186	24 (14–47)	1481 (898–2217)
Abdomen			
Low dose			
Colonography	9933	4 (3–5)	429 (298–532)
Suspected renal stones	49 233	9 (6–15)	493 (323–797)
Bladder (without contrast material)	18 130	11 (7–14)	614 (396–790)
Routine dose			
Abscess	302	11 (7–17)	444 (268–766)
Abdomen routine, not otherwise specified	884 106	11 (8–17)	640 (412–1022)
Gastrointestinal tract evaluation, enterography	29 846	10 (7–15)	517 (354–864)
Trauma	19 518	15 (10–21)	833 (517–1405)
Angiography	36 705	11 (7–15)	1117 (675–1801)
Liver, not otherwise specified	25 016	10 (7–16)	1151 (600–2007)
High dose			
Adrenal nodule	353	12 (9–15)	397 (227–684)
Fistula	54	9 (6–13)	615 (464–910)
Angiography for aortic injury†	8220	7 (4–12)	667 (365–1240)
Transplant	2832	7 (6–10)	704 (468–1086)
Bladder with contrast	4993	10 (6–15)	1187 (544–2014)
Pancreas	9702	11 (8–16)	1171 (753–1777)
Hepatocellular and biliary cancers	6595	9 (6–14)	1276 (824–2024)

Table 4 (*continues*)

Table 4: (*continued*) Median, 25th, and 75th Percentiles of DLP and $CTDI_{vol}$ for Each Clinical Indication for Head, Chest, Cardiac, Abdomen, and Combined Head and Neck Body Regions

CT Category and Indication	No. of Examinations	$CTDI_{vol}$*	DLP*
Metastatic cancers	2827	15 (10–20)	1074 (811–1411)
Urography	32 287	11 (8–16)	1144 (710–1817)
Acute gastrointestinal bleeding	3560	10 (7–15)	1310 (834–2060)
Abdominal run-off	10 025	8 (6–11)	1386 (991–2147)
Renal mass	9436	14 (10–19)	1633 (1069–2337)
Combined head and neck			
Routine dose			
Routine dose head combined with any neck and/or cervical spine	88 106	21 (14–32)	957 (580–1309)
High dose			
High dose head combined with any neck and/or cervical spine	10 078	145 (99–262)	2547 (1676–3646)

Note.—$CTDI_{vol}$ = volume CT dose index, DLP = dose-length product.

* Numbers are medians, with interquartile ranges (25th and 75th percentiles) in parentheses.

† Angiography for aortic injury includes rupture, dissection, and endovascular leak.

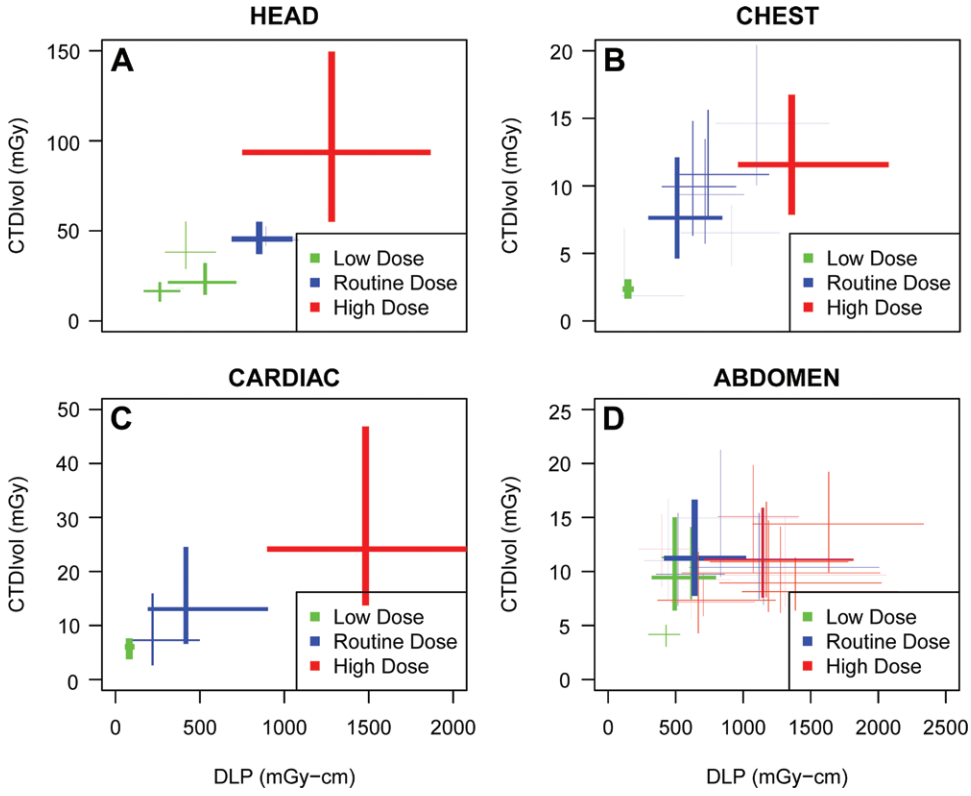

Figure 2: Graphs show volume CT dose index ($CTDI_{vol}$) and dose-length product (DLP) for each indication that comprises **(A)** head, **(B)** chest, **(C)** abdomen, and **(D)** cardiac CT categories. Length of arms in cross show interquartile range in radiation dose. Intersection of arms is median for $CTDI_{vol}$ and DLP, number of lines reflects number of indications in category, and line thickness is proportional to number of examinations in category. For each indication, $CTDI_{vol}$ is defined as mean $CTDI_{vol}$ across all irradiating events weighted by scanning length, and DLP value is summation across all irradiating events. For example, in three-phase study, where each phase (ie, irradiating event) had average $CTDI_{vol}$ of 10 mGy, scanning length of 50 cm, and DLP of 500 mGy · cm, study would be shown in plot as average weighted $CTDI_{vol}$ of 10 mGy and total DLP of 1500 mGy · cm.

dose chest (753 583 examinations), and routine dose abdomen (1 002 264 examinations)—accounted for 62% of all CT examinations. Given this frequency, optimizing acquisition protocols in these three categories alone could have a substantial impact on reducing overall radiation exposure from CT examinations.

For the purpose of comparing radiation doses across facilities, assessing doses within broad CT categories based on clinical indication is more informative than assessing doses within protocols. Dose assessment within protocol groups ignores the primary factor determining dose (ie, protocol selection), which is almost entirely at the discretion of the radiologist. Assessing doses in this way, without considering the underlying indication, ignores the variation that occurs due to protocol choice and fails to identify patients who require a particular protocol, such as single-phase abdomen, but who instead received much higher doses through unnecessary multiphase examinations. Radiation doses should be assessed based on the intent and clinical question of the provider ordering the examination, not on the radiologist's choice of protocol.

The data for this study were pulled from the University of California San Francisco registry, but other data sources, such as the larger American College of Radiology Dose Index Registry, could be used to similarly categorize CT examinations based on the indications that led to the examinations and then to create radiation dose benchmarks for those categories (12). Because the existing American College of Radiology benchmarks are created according to protocol (1), rather than according to clinical

Table 5: Variation within Indications versus between Indications for CT Categories and within Categories versus between Categories within Body Regions

	Variation between Indications within CT Category				Variation between CT Categories			
Location and Dose	Mean Square within Indications	Mean Square between Indication within CT Category	Between versus Within (*F* value)	Ratio of *F* Value to N	Mean Square within CT Category	Mean Square between CT Categories within Body Region	Between versus Within (*F* value)	Ratio of *F* Value to N
Head					175 236	16 976 982 486	96 881	0.10
Low dose	142 076	633 014 914	4455	0.04				
Routine dose	121 079	127 912 884	1056	0.00				
High dose*	NC	NC	NC	NC				
Chest					161 216	2 451 443 505	15 206	0.02
Low dose*	NC	NC	NC	NC				
Routine dose	162 960	618 213 847	3794	0.01				
High dose*	NC	NC	NC	NC				
Abdomen					308 649	14 395 193 179	46 639	0.05
Low dose	107 303	54 353 482	507	0.01				
Routine dose	260 005	1 082 879 111	4165	0.00				
High dose	738 482	385 328 496	522	0.01				
Cardiac					316 698	3 997 851 468	13 342	0.26
Low dose*	NC	NC	NC	NC				
Routine dose	315 257	482 266 188	1530	0.05				
High dose*	NC	NC	NC	NC				

Note.—$P < .001$ for all statistical comparisons. N = number of examinations, NC = not calculated.

* Each of these CT categories had only one indication; thus, these values were NC.

indication as described herein, it is not possible to directly compare observed doses. However, given the similarity in how CT examinations are assembled in the University of California San Francisco and American College of Radiology registries, it would be worthwhile to compare benchmarks based on indications across the registries.

For some CT categories, the observed doses reflect optimized levels. For example, the median $CTDI_{vol}$ for low dose chest is 2 mGy, consistent with the American College of Radiology benchmarks (16). For other categories, the observed doses are not optimized. For example, for abdomen low dose, where 64% of examinations assessed renal calculi, the median in $CTDI_{vol}$ was 9 mGy, higher than the optimum of less than 4 mGy (17). The consistency in doses for CT examinations performed for lung cancer screening with American College of Radiology benchmarks may be driven by the fact that reporting is required by the Centers for Medicare and Medicaid Services for reimbursement. The inconsistency in doses for suspected renal stone imaging is consistent with previously reported deviation between observed and optimum practice (9,18). Although the proposed framework does not provide optimized dose levels because actual practice is often not optimized, adoption of this simplified approach for assessing radiation doses may nevertheless contribute to dose improvement over time by allowing consistent measurement of current practice.

A potential application of the framework is in meeting standards of regulators and accreditors. For example, the Joint Commission requires that hospitals ensure patients receive appropriate imaging based on their clinical indication for scanning and review of incidents in which the radiation dose delivered exceeds the expected dose for that protocol (19). This standard requires hospitals to have a system to both assign patients to protocols and to generate radiation dose thresholds for each protocol; however, there is no consistent standard used across hospitals. We believe that our approach could provide a simpler and more effective solution for comparing radiation doses across institutions, leading to dose optimization and ultimately a reduction in excessively high radiation doses.

This study's main strengths include its large sample size and inclusion of the majority of CT examinations from diverse imaging facilities. The study had several limitations. First, a large number of CT examinations in the registry were for "routine" purposes and where indication was not specified. However, because our primary aim was to identify examinations that required radiation doses that were not routine (ie, high or low), the inability to identify a precise indication for examinations considered routine does not undermine the approach. If there were multiple clinical indications for CT, the examination was assigned to the higher dose category. Although this may have added imprecision, excluding such examinations would have inflated the differences between groups; thus, their inclusion was conservative.

Nearly all diagnostic CT examinations in the present study can be assigned to one of the identified categories. Nonetheless, facilities may need to create additional protocols if they have patients with unique needs not captured in the indications that

we observed. The categories were created in part based on expert opinion and face validity rather than on evidence associated with diagnostic accuracy; thus, additional research is needed to determine the minimum required image quality for diagnostic accuracy for each indication. As the framework is applied, refinements might include combining or subdividing some of the 19 categories. The assignment of examinations to the CT categories based on Digital Imaging and Communications in Medicine metadata has inaccuracies; 408 176 examinations (approximately 10%) were misclassified in our assessment. The accuracy of assigning examinations to CT categories based on clinical indication may be improved using information extracted from the electronic health record associated with the study order. Finally, sites contributing to the registry use a single-dose management software, which could introduce bias if sites that use such monitoring programs pay closer attention to radiation use.

Based on the large data set of the University of California San Francisco International CT Dose Registry, we established a framework to assess radiation doses. These categories may offer imaging facilities a consistent, simplified approach to radiation dose assessment, optimization, and reduction of unintended harm.

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