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How do cancer-specific CT protocols compare to the ACR dose index registry? An analysis of CT dose at two cancer centers

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Abstract

Background: Little guidance exists on how to stratify radiation dose according to diagnostic task. Changing dose for different cancer types is currently not informed by the ACR DIR dose survey.

Methods: A total of 9,602 patient examinations were pulled from two NCI designated cancer centers. CT dose ($CTDI_{vol}$) was extracted, and patient water equivalent diameter was calculated. N-way anova was used to compare the dose levels between two protocols used at Site 1, and three protocols used at Site 2.

Results: Sites 1 and 2 both independently stratified their doses according to cancer indications in similar ways. For example, both sites used lower doses ($p<0.001$) for follow-up of testicular cancer, leukemia, and lymphoma. Median dose at median patient size from lowest to highest dose level for Site 1 were 17.9 [17.7, 18.0] mGy (mean with 95% confidence interval) and 26.8 [26.2, 27.4] mGy. For Site 2, they were 12.1 [10.6, 13.7] mGy, 25.5 [25.2, 25.7] mGy and 34.2 [33.8, 34.5]. Both sites had higher doses ($p<0.001$) between their routine and high image quality protocols, with an increase of 48% between these doses for Site 1 and 25% for Site 2. High image quality protocols were largely applied for detection of low contrast liver lesions or subtle pelvic pathology.

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Dr. Sean Rose provided statistical advice for this paper.

Written informed consent was waived by the Institutional Review Board.

Institutional Review Board approval was obtained.

No study subjects or cohort data overlap with other publications.

Methodology is retrospective cross-sectional study.

This is a multicenter study.

Conclusions: We demonstrated two cancer centers independently choose to stratify their cancer doses in similar ways. Site 1 and 2 dose data were higher than the ACR DIR dose survey data. We thus propose including a cancer specific subset for the dose registry.

Summary Sentence:

Dose surveys that collect data by body region do not capture dose stratification used by cancer centers to tailor dose to specific cancer indications.

Keywords

Diagnostic Reference Levels; radiation; oncology; CT Dose

Introduction

Over the last decade, there has been a progressive increase in CT utilization for many clinical indications, cancer surveillance foremost among them [1,2]. For a variety of reasons, CT is the preferred cross-sectional imaging modality in the work-up of most malignancies [3–8]. During the course of cancer treatment, patients will undergo multiple CT scans [9, 10], with the frequency and timing varying with the patient's disease and clinical trajectory. With ongoing awareness and concern related to the risk of radiation exposure, particularly in patients receiving serial exams [10, 11], there has been a focus on radiation dose reduction. Even though no studies have ever demonstrated serial CT exams impart an increased cancer risk to patients. This has been recently augmented by the introduction of advanced CT image reconstruction technology, including artificial intelligence and deep learning-based applications [12]. Imaging of aggressive or metastatic cancer has been swept along in this dose reduction movement, but there is data and clinical context suggesting that this should be reconsidered in this patient population [13]. Aggressive radiation dose reduction can have a negative impact on cancer detection and result in inaccurate staging [14]. Figures 1 and 2 depict examples of this by comparing scans of the same patient imaged using lower-dose "routine" abdomen protocols and higher-dose dedicated cancer imaging protocols.

In the clinical context of metastatic cancer, accurate detection, characterization and staging of disease is of paramount importance. Accurate imaging assessment of treatment response is the foundation for subsequent treatment planning. Given the relatively low risk and extended time it may take for the development of an imaging study related neoplasm [9], aggressive radiation dose reduction in this patient population is not appropriate and counter-productive. For example, Zondervan *et al.* 2013 concluded "Among young adults undergoing body CT, risk of death from underlying morbidity is more than an order of magnitude greater than death from long-term radiation-induced cancer." [9] CT protocol settings, especially radiation dose, should be specifically tailored to the clinical concern. For various clinical indications, CT protocol priorities and standards should be adjusted to result in several tiers of radiation dose across the spectrum of clinical conditions. Cancer patients would be better served with a tiered radiation dose system, based on the anatomic location and the stage of their disease. For example, image quality can be lower for patients with lymphoma or testicular cancer where disease is often nodal and readily detectable versus patients with metastatic liver disease (i.e., often a subtle, low contrast detection task). [15]

However, the radiology community has thus far not systematically applied dose stratification and standards for this cancer specific clinical context. Although there are robust radiation dose registries available through the ACR [16, 17] and EU countries [18, 19], there is little data to define the appropriate dose in cancer patients. There has been some discussion in expanding radiation dose registries to be specific to clinical indication and even specific to CT vendors/platforms, but currently available data remains undifferentiated [20–22].

The purpose of this study was to demonstrate how two cancer centers have chosen to stratify radiation dose for their patients. These doses are compared to the ACR dose registry to demonstrate the incongruence of cancer specific and general body region specific dose data, thereby providing support for the creation of a cancer specific subset of the dose registry.

Methods

Two institutions, the University of Wisconsin Madison (herein referred to as Site 1) and MD Anderson Cancer Center (herein referred to as Site 2), each an NCI designated comprehensive cancer center, retrospectively reviewed CT radiation doses used for cancer imaging in the abdomen. The study was approved by our institutional review boards as Health Insurance Portability and Accountability Act compliant, and written informed consent was waived.

Dose data from Site 1 was extracted using a commercial product (Imalogix LLC, Bryn Mawr, PA USA). Dose data from Site 2 was extracted using a different commercial product (Radimetrics, Whippany NJ USA). Each dose monitoring product produced the same data fields: patient size as effective diameter, protocol name, and series level $CTDI_{vol}$. Effective diameter values were converted [23] to water equivalent diameter (WED) to facilitate comparison to ACR Dose Index Registry data [16]. ACR DIR achievable dose (i.e., median dose data at a given patient size) data was taken from Table 6 of Reference [16] (Kanal 2017) for the indication “Abdomen and Pelvis with contrast material”.

N-way anova was used to evaluate the effect of institution (Site 1 versus Site 2) and WED on $CTDI_{vol}$ for each protocol at each institution. A description of the two protocols used at Site 1 and the three protocols used at Site 2 for cancer imaging are provided in Table 1. Scan parameters for these protocols are provided in Table 2. We define significance as $p<0.05$. To compute the dose for a given protocol at a specific patient size, for each institution we fit each protocol’s $CTDI_{vol}$ versus WED data using the model $CTDI_{vol} = k1*\exp(k2 * WED) + k3$ where k1, k2, and k3 are fitting coefficients. This model can predict all major CT vendor’s automatic exposure system’s response curves [24]. This model would not work in the condition that a site used drastically different dose prescriptions for patients of different sizes. Fit values and 95% interval confidence intervals were calculated using a non-linear fitting and prediction routine (*nlinfit* and *nlpredci* functions, Matlab, Natick, MA USA).

In addition to evaluating each institution’s protocols at patient sizes matching the ACR DIR report, we also calculated them at the median patient size for all patients from Site 1 and Site 2. Each site’s median patient value was included because we noted a systematic shift in patient size distributions between Site 1 and Site 2, which we attribute to differences in

the commercial dose monitoring software's size calculations. Therefore, we also calculated 5%−95% percentiles of the dose data for each protocol at each institution and the ACR DIR data to characterize the dose data without the influence of a potentially incorrect patient size value derived from the commercial dose monitoring solutions.

Results

A total of 4,667 examinations were pulled from Site 1; 4,004 from a routine abdominal cancer protocol, and 663 from a high-image-quality (HIQ) cancer protocol. The Site 1 data was acquired between November 2020 and June 2021. A total of 4,935 examinations were pulled from Site 2; 37 from a low dose abdomen cancer protocol, 2,944 from a routine abdominal cancer protocol, and 1,954 from a HIQ cancer protocol. The Site 2 data was acquired between November 2020 and July 2021. Age and gender were not available from either institution's data.

Figure 3 depicts all 5 cancer imaging protocols with the ACR DIR data overlaid. Tables 3 and 4 describe the dose data using the non-linear fitting routine and percentile calculations respectively. Statistical testing results between the institutional protocols is shown in Table 5, where all protocols were statistically significantly different except for the Site 1 routine to Site 2 low-dose protocol. As expected, for each institution, dose increased with both patient size and when moving from low-dose to routine, or routine to HIQ. For example, the Site 1 median dose (50th percentile values from Table 4) went from 17.5 to 25.9 mGy from the Site 1 routine to Site 1 HIQ protocols. Similarly, the Site 2 low-dose, routine, and HIQ median doses increased as 12.9, 25.5, and 31.9 mGy respectively.

The median patient size for Site 1 data was 348 mm WED. Doses for site 1 at its median patient size were: Site 1 routine 17.9 [17.7 18.0] (mean and 95% confidence interval) mGy and Site 1 HIQ 26.8 [26.2 27.4] mGy. The median patient size for Site 2 data was 307 mm WED. Doses for Site 2 at its median size were: Site 2 low dose 12.1 [10.6 13.7] mGy, Site 2 routine 25.5 [25.2 25.7] mGy, and site 2 HIQ 34.2 [33.8 34.5] mGy.

Discussion:

Our results demonstrate that both cancer centers independently adopted similar radiation dose levels for cancer imaging. Doses for both sites increase with patient size as needed to provide consistent diagnostic image quality [24–26]. Both sites demonstrate plateauing of the dose data at small and large patient sizes due to the CT scanner mA minimums and/or maximums respectively [27]. Comparison of the ACR DIR achievable dose data to both sites' data from Figure 3 or Tables 3 and 4 demonstrate that while the routine protocol from Site 1 and the low dose protocol from Site 2 are close to the ACR DIR data, each site's higher dose level protocols exceed the ACR DIR values. For example, the 50^{th} percentile of the ACR DIR data was 12 mGy, compared to 17.5 and 25.5 mGy at Site 1 and at Site 2 for routine protocols, respectively. The Site 1 HIQ 50th percentile dose was 13.9 mGy higher than the ACR DIR median value (i.e., 25.9 versus 12 mGy), and the Site 2 HIQ median dose was 19.9 mGy (31.9 versus 12 mGy) higher than the ACR DIR median value.

This study mirrors the work of Brat *et al.* 2019 who also demonstrated indication-based differences within a body region for CT dose [22]. Brat *et al.* 2019 concluded their study with a call for action in creating more indication specific dose registries: "…this study suggests the necessity of estimating diagnostic reference levels based on clinical indication, especially for abdomen exams. Institutions that are fostering continuous dose optimization and local clinical diagnostic dose reference levels should consider defining protocols based on clinical indication and BMI class, to achieve ALARA." [22] Our results concur with Brat *et al.*'s findings for cancer specific indications and demonstrate even larger ranges in CT dose within the same body region.

The N-way anova analysis presented in Table 5 demonstrates that dose stratification and indication specific protocols in use at Sites 1 and 2 result in statistically significant dose increases when moving from the Site 1 routine to HIQ dose level and from the Site 2 low-dose to routine and routine to high-image-quality levels. For Site 1, the HIQ cancer protocol increased the dose over the routine protocol by 48% (e.g., from Table 4, the median dose increased from 17.5 to 25.9 mGy). This change reflects the increased image quality demands for patients at risk for subtle metastatic disease, often most challenging to detect in the liver. The Site 1 HIQ protocol used for most oncologic indications closely matches the routine protocol used at Site 2, a dedicated oncologic center. Within the dedicated oncologic practice of Site 2, a HIQ protocol version represents a 25% increase in median dose from the Site 2 routine and the Site 2 low dose protocol represents an approximate 50% reduction in radiation dose from routine.

It is well known in the radiology community that regional and institution specific CT dose preferences exist for CT imaging. [28–30] Our study agrees with previous observations that sites have different dose levels for the same indication. The values from this report are not intended as a reference for other institution's cancer specific dose protocol dose levels. Our study demonstrates how two academic cancer imaging centers independently and simultaneously evolved a stratified dose approach incorporating higher dose protocols for the visualization of more subtle disease.

It is reasonable that the effort of two independent CT protocols optimization teams [31–35] would iterate to the same solutions. Table 1 demonstrates that both Sites 1 and 2 use size-based protocols. This stratification of patients into different size bins corresponds with a dose increase as one moves from smaller to larger body habitus (e.g., from small to medium to large), but this dose increase is related only to patient size. The dose differences accounting for size, are present for both sites, regardless of indication or protocol type. CT protocol teams at Sites 1 and 2 created size-based protocols in order to optimize technical scan parameters as a function of patient size to keep scans faster for smaller patients, use a dose optimized kV across patient size [36–37], and slower scan speed to deliver the higher doses needed for the bariatric patient population. The dose stratification and CT scanner automatic exposure control adjustments for Site 1 have been previously published [27].

At Site 2, the routine cancer protocol is applied across most cancer types. Site 2 has a protocol dose level below routine (i.e., low dose from Table 1) for the follow-up of treated leukemia/lymphoma and treated testicular cancer and a higher dose protocol (i.e., HIQ

from Table 1) mainly for colorectal carcinoma. Colorectal carcinoma patients often have low contrast liver lesions which must be carefully evaluated to determine whether surgical resection or targeted therapy is the proper treatment [38]. Site 2 also uses their higher dose routine protocol in patients undergoing non-contrast examinations unless the clinical query is simply regarding genitourinary calculi. The use of higher dose in non-contrast scans is an attempt to glean staging information from a limited examination due to the lack of IV contrast. Site 2's emergency and inpatients scans of patients with potential superimposed acute etiologies in complex cancer cases additionally utilize the higher dose protocol.

Comparing the indication mapping between Sites 1 and 2, both sites use higher radiation dose for oncologic indications that may present with low contrast lesions. The routine cancer protocol used at Site 1 is also routinely used for evaluation of abdominal pain or possible infection. Site 1's routine protocol is also used in patients with low risk of lymphoma or testicular cancer recurrence or with higher conspicuity lesions (nodes, bone lesions, spleen) if recurring. The HIQ cancer protocol at Site 1 maps to clinical cancer imaging tasks similar to the routine protocol at Site 2 (see Table 1). There is no additional higher radiation dose protocol at Site 1 to compare to the HIQ protocol used at Site 2. Therefore, the closest matching protocols, from an indication mapping perspective, between Sites 1 and 2 would be the HIQ protocol of Site 1 to the routine protocol of Site 2. If we compare the median and 95% prediction intervals of dose data at Sites 1 and 2 at their respective median patient sizes, we see good agreement between dose values. For example, Site 1's HIQ dose was 26.8 [26.2 27.4] mGy compared to Site 2's routine dose of 25.5 [25.2 25.7] mGy.

Currently existing dose registries do not consider clinical indication and task for cancer imaging. Most registries only delineate the general body region and the presence or absence of an intravenous contrast agent. While the currently aggregated dose values (i.e., the dose values one sees in a dose survey report) may be appropriate for many indications, we posit that cancer patients as a group warrant unique consideration when creating scan parameters and prescribing radiation dose. Doses in the range of the HIQ at Site 1 or routine protocol at Site 2 may be more appropriate for patients at risk for hepatic metastatic disease or other potentially subtle cancer related pathology. Both institutions prescribe lower radiation doses for higher contrast imaging tasks like detection of nodal disease in lymphoma/leukemia or testicular cancer (routine at Site 1, low dose at Site 2). In addition, patients with the latter two conditions are often younger and undergo surveillance even when there is no evidence of disease, which also makes this lower dose prescription more appropriate. Having focused dose registry data that sets higher radiation dose standards for low contrast tasks in the ranges demonstrated in this study will validate a more realistic and appropriate dose range for these patients. It is challenging to apply a one 'size' fits all approach to cancer patients, as clearly there are indications for which lower dose remains reasonable, so using a tiered approach as demonstrated here and as could be incorporated into cancer-specific dose registries would be warranted. Data presented here could serve as a starting point for such a registry, but clearly additional data and study is needed for a robust cancer-specific dose registry.

Using currently existing iterative reconstruction (IR) techniques, dose reduction that can be achieved without compromising accuracy has probably been maximized in the modest range

[38]. There have been a series of studies looking at the detection of low contrast liver lesions with decreasing radiation dose. A review of this literature was conducted by Mileto *et al.* 2019 who concluded “Radiologists need to be aware that use of IR can result in a decline of spatial resolution for low-contrast structures and degradation of low-contrast detectability when radiation dose reductions exceed approximately 25%”, [39] supporting the idea that one cannot necessarily achieve the higher levels of image quality needed for some cancer indications simply by applying IR methods to routine abdominal (i.e., non-cancer) protocols. The potential of deep learning/artificial intelligence (DL/AI) based techniques is still an emerging area of investigation, with early studies show marked reduction in noise and improved contrast to noise ratio with improved image quality compared to conventional IR methods [12, 40–45].

Limitations to this study include different dose monitoring solutions used to extract radiation dose data at sites 1 and 2. The median WED of sites 1 and 2 was 348 and 307 mm respectively. This difference of roughly 4 cm is visible in the scatter plot of doses in Figure 3. From Figure 3, the largest sized patients at Site 1 were in the 450–500 mm WED range, whereas Site 2 showed the largest patients in the 400–450 mm WED range. It is unlikely the largest patients between two cancer centers within the USA would have such a difference. This size difference makes comparing doses from Figure 3 or Table 3 difficult, given doses on Figure 3 and Table 3 are compared using size. Our belief is that the different dose monitoring systems have a systematic shift in their values, thus we did not report size specific dose estimates (SSDE) in this paper; SSDE depends on patient size measurements. Due to this possible systematic patient size issue, we feel the radiation dose data from our study is more appropriately compared using each site’s percentile data as reported in Table 4. However, direct comparison of doses at the two sites is not meant to be the focus of this work.

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Abbreviations:

CT	Computed Tomography
CTDIvol	Computed Tomography Dose Index
ACR DIR	American College of Radiology Dose Index Registry
EU	European Union
NCI	National Cancer Institute
WED	water equivalent diameter
HIQ	high image quality

References

1. Moreno CC, Hemingway J, Johnson AC, Hughes DR, Mittal PK, Duszak R Jr. Changing Abdominal Imaging Utilization Patterns: Perspectives From Medicare Beneficiaries Over Two Decades. J Am Coll Radiol 2016;13:894–903. [PubMed: 27084072]
2. Smith-Bindman R, Kwan ML, Marlow EC, et al. Trends in Use of Medical Imaging in US Health Care Systems and in Ontario, Canada, 2000–2016. JAMA 2019;322:843–56. [PubMed: 31479136]
3. Casalino DD, Remer EM, Bishoff JT, Coursey CA, Dighe M, Harvin HJ, … & Weinfeld RM (2014). ACR appropriateness criteria post-treatment follow-up of renal cell carcinoma. Journal of the American College of Radiology, 11(5), 443–449. [PubMed: 24793039]
4. Fowler KJ, Kaur H, Cash BD, Feig BW, Gage KL, Garcia EM, … & Carucci LR (2017). ACR appropriateness criteria® pretreatment staging of colorectal cancer. Journal of the American College of Radiology, 14(5), S234–S244. [PubMed: 28473079]
5. Kang SK, Reinhold C, Atri M, Benson CB, Bhosale PR, Jhingran A, … & Glanc P (2018). ACR appropriateness criteria® staging and follow-up of ovarian cancer. Journal of the American College of Radiology, 15(5), S198–S207. [PubMed: 29724422]
6. Eisenhauer Elizabeth A., Therasse Patrick, Bogaerts Jan, Schwartz Lawrence H., Sargent Danielle, Ford Robert, Dancey Janet et al. “New response evaluation criteria in solid tumours: revised RECIST guideline (version 1.1).” European journal of cancer 45, no. 2 (2009): 228–247. [PubMed: 19097774]
7. Therasse Patrick, Arbuck Susan G., Eisenhauer Elizabeth A., Wanders Jantien, Kaplan Richard S., Rubinstein Larry, Verweij Jaap et al. “New guidelines to evaluate the response to treatment in solid tumors.” Journal of the National Cancer Institute 92, no. 3 (2000): 205–216. [PubMed: 10655437]
8. Benson Al B., Venook Alan P., Al-Hawary Mahmoud M., Arain Mustafa A., Chen Yi-Jen, Ciombor Kristen K., Cohen Stacey et al. “Colon cancer, version 2.2021, NCCN clinical practice guidelines in oncology.” Journal of the National Comprehensive Cancer Network 19, no. 3 (2021): 329–359. [PubMed: 33724754]
9. Zondervan RL, Hahn PF, Sadow CA, Liu B, & Lee SI (2013). Body CT scanning in young adults: examination indications, patient outcomes, and risk of radiation-induced cancer. Radiology, 267(2), 460–469. [PubMed: 23386731]
10. Sodickson A, Baeyens PF, Andriole KP, Prevedello LM, Nawfel RD, Hanson R, & Khorasani R (2009). Recurrent CT, cumulative radiation exposure, and associated radiation-induced cancer risks from CT of adults. Radiology, 251(1), 175–184. [PubMed: 19332852]
11. Brambilla M, Vassileva J, Kuchcinska A, & Rehani MM (2020). Multinational data on cumulative radiation exposure of patients from recurrent radiological procedures: call for action. European radiology, 30(5), 2493–2501. [PubMed: 31792583]
12. Mohammadinejad P, Mileto A, Yu L, Leng S, Guimaraes LS, Missert AD, Jensen CT, Gong H, McCollough CH, Fletcher JG (2021) CT Noise-Reduction Methods for Lower-Dose Scanning: Strengths and Weaknesses of Iterative Reconstruction Algorithms and New Techniques. Radiographics 41 (5):1493–1508. doi:10.1148/rg.2021200196 [PubMed: 34469209]
13. Brenner DJ, Shuryak I, Einstein AJ. Impact of reduced patient life expectancy on potential cancer risks from radiologic imaging. Radiology 2011;261:193–8. [PubMed: 21771956]
14. Pooler BD, Lubner MG, Kim DH, et al. Prospective Evaluation of Reduced Dose Computed Tomography for the Detection of Low-Contrast Liver Lesions: Direct Comparison with Concurrent Standard Dose Imaging. Eur Radiol 2017;27:2055–66. [PubMed: 27595834]
15. Jensen CT, Wagner-Bartak NA, Vu LN, et al. Detection of Colorectal Hepatic Metastases Is Superior at Standard Radiation Dose CT versus Reduced Dose CT. Radiology 2019;290:400–9. [PubMed: 30480489]
16. Kanal KM, Butler PF, Sengupta D, Bhargavan-Chatfield M, Coombs LP, & Morin RL (2017). US diagnostic reference levels and achievable doses for 10 adult CT examinations. Radiology, 284(1), 120–133. [PubMed: 28221093]
17. Morin RL, Coombs LP, & Chatfield MB (2011). ACR dose index registry. Journal of the American College of Radiology, 8(4), 288–291. [PubMed: 21458770]

18. European Society of Radiology (ESR) communications@myESR.org. (2015). Summary of the European Directive 2013/59/Euratom: essentials for health professionals in radiology. Insights into imaging, 6, 411–417. [PubMed: 26014053]
19. Moghadam N, Lecomte R, Mercure S, Rehani MM, & Nassiri MA (2021). Simplified size adjusted dose reference levels for adult CT examinations: A regional study. European Journal of Radiology, 142, 109861. [PubMed: 34280596]
20. Tsapaki V, Damilakis J, Paulo G, et al. CT diagnostic reference levels based on clinical indications: results of a large-scale European survey. Eur Radiol 2021;31:4459–69. [PubMed: 33449177]
21. Paulo G, Damilakis J, Tsapaki V, et al. Diagnostic Reference Levels based on clinical indications in computed tomography: a literature review. Insights into imaging 2020;11:96. [PubMed: 32804275]
22. Brat H, Zanca F, Montandon S, et al. Local clinical diagnostic reference levels for chest and abdomen CT examinations in adults as a function of body mass index and clinical indication: a prospective multicenter study. Eur Radiol 2019;29:6794–804. [PubMed: 31144074]
23. Burton CS, & Szczykutowicz TP (2018). Evaluation of AAPM Reports 204 and 220: estimation of effective diameter, water-equivalent diameter, and ellipticity ratios for chest, abdomen, pelvis, and head CT scans. Journal of applied clinical medical physics, 19(1), 228–238. [PubMed: 29178549]
24. Chapter 7 Automatic Exposure Control. Szczykutowicz T (2020). The CT Handbook: Optimizing Protocols for Today's Feature-rich Scanners. Medical Physics Publishing.
25. Mulkens Tom H., Bellinck Patrick, Baeyaert Michel, Ghysen Dirk, Xavier Van Dijck Elvier Mussen, Venstermans Caroline, and Termote Jean-Luc. "Use of an automatic exposure control mechanism for dose optimization in multi–detector row CT examinations: clinical evaluation." Radiology 237, no. 1 (2005): 213–223. [PubMed: 16126917]
26. Söderberg Marcus, and Gunnarsson Mikael. "Automatic exposure control in computed tomography–an evaluation of systems from different manufacturers." Acta radiologica 51, no. 6 (2010): 625–634. [PubMed: 20429764]
27. Szczykutowicz Timothy P., Bour Robert K., Rubert Nicholas, Wendt Gary, Pozniak Myron, and Ranallo Frank N.. "CT protocol management: simplifying the process by using a master protocol concept." Journal of applied clinical medical physics 16, no. 4 (2015): 228–243.
28. Parakh Anushri, Euler Andre, Szucs-Farkas Zsolt, and Schindera Sebastian T.. "Transatlantic comparison of CT radiation doses in the era of radiation dose–tracking software." American Journal of Roentgenology 209, no. 6 (2017): 1302–1307. [PubMed: 28898129]
29. Koller CJ, Eatough JP, & Bettridge A (2003). Variations in radiation dose between the same model of multislice CT scanner at different hospitals. The British journal of radiology, 76(911), 798–802. [PubMed: 14623781]
30. Smith-Bindman Rebecca, Wang Yifei, Chu Philip, Chung Robert, Einstein Andrew J., Balcombe Jonathan, Cocker Mary et al. "International variation in radiation dose for computed tomography examinations: prospective cohort study." Bmj 364 (2019).
31. Szczykutowicz T, and Myron P. "A team approach for CT protocol optimization." Radiol. Manage 38, no. 2 (2016): 19–23.
32. Szczykutowicz TP, Bour RK, Pozniak M, & Ranallo FN (2015). Compliance with AAPM Practice Guideline 1. a: CT Protocol Management and Review—from the perspective of a university hospital. Journal of applied clinical medical physics, 16(2), 443–457.
33. Kofler JM, Cody DD, & Morin RL (2014). CT protocol review and optimization. Journal of the American College of Radiology, 11(3), 267–270. [PubMed: 24589402]
34. Cody DD, Fisher TS, Gress DA, Layman RR Jr, McNitt-Gray MF, Pizzutiello RJ Jr, & Fairobent LA (2013). AAPM medical physics practice guideline 1. a: CT protocol management and review practice guideline. Journal of applied clinical medical physics, 14(5), 3–12. [PubMed: 24036879]
35. Jensen CT, Javadi S, Bhosale P, Moawad AW, Saleh M, Ganeshan D, Morani AC. Computed tomography technologist notes in PACS to radiologists: what are they telling us and how does it increase value? Abdom Radiol (NY). 2021 Jun;46(6):2913–2919. doi: 10.1007/s00261-021-02962-8. Epub 2021 Feb 7. [PubMed: 33550526]

36. Yu L, Li H, Fletcher JG, & McCollough CH (2010). Automatic selection of tube potential for radiation dose reduction in CT: a general strategy. Medical physics, 37(1), 234–243. [PubMed: 20175486]

37. Kalender WA, Deak P, Kellermeier M, van Straten M, & Vollmar SV (2009). Application-and patient size-dependent optimization of x-ray spectra for CT. Medical physics, 36(3), 993–1007. [PubMed: 19378760]

38. Volders D, Bols A, Haspeslagh M, Coenegrachts K. Model-based iterative reconstruction and adaptive statistical iterative reconstruction techniques in abdominal CT: comparison of image quality in the detection of colorectal liver metastases. Radiology 2013;269:469–74. [PubMed: 23847252]

39. Mileto A, Guimaraes LS, McCollough CH, Fletcher JG, & Yu L (2019). State of the art in abdominal CT: the limits of iterative reconstruction algorithms. Radiology, 293(3), 491–503. [PubMed: 31660806]

40. Jensen CT, Liu X, Tamm EP, et al. Image Quality Assessment of Abdominal CT by Use of New Deep Learning Image Reconstruction: Initial Experience. AJR Am J Roentgenol 2020;215:50–7. [PubMed: 32286872]

41. Szczykutowicz TP, Nett B, Cherkezyan L, et al. Protocol Optimization Considerations for Implementing Deep Learning CT Reconstruction. AJR Am J Roentgenol 2021;216:1668–77. [PubMed: 33852337]

42. Greffier J, Hamard A, Pereira F, Barrau C, Pasquier H, Beregi JP, & Frandon J (2020). Image quality and dose reduction opportunity of deep learning image reconstruction algorithm for CT: a phantom study. European Radiology, 1–9.

43. Higaki T, Nakamura Y, Zhou J, Yu Z, Nemoto T, Tatsugami F, & Awai K (2020). Deep Learning Reconstruction at CT: Phantom Study of the Image Characteristics. Academic Radiology, 27(1), 82–87. [PubMed: 31818389]

44. Singh R, Digumarthy SR, Muse VV, et al. Image Quality and Lesion Detection on Deep Learning Reconstruction and Iterative Reconstruction of Submillisievert Chest and Abdominal CT. AJR Am J Roentgenol 2020;214:566–73. [PubMed: 31967501]

45. Cao L, Liu X, Li J, et al. A study of using a deep learning image reconstruction to improve the image quality of extremely low-dose contrast-enhanced abdominal CT for patients with hepatic lesions. Br J Radiol 2021;94:20201086.

Key Points

1. While differing in absolute dose values, two different cancer centers chose to stratify their CT radiation dose levels in a similar indication-specific manner.
2. The principles of ALARA motivated both centers to develop higher dose protocols for more subtle cancer findings (e.g., colorectal cancer) and lower dose protocols more readily detectable findings (i.e., follow-up of treated leukemia/lymphoma).
3. The existing ACR DIR registry data does not take into account the higher dose requirements of cancer specific protocols.

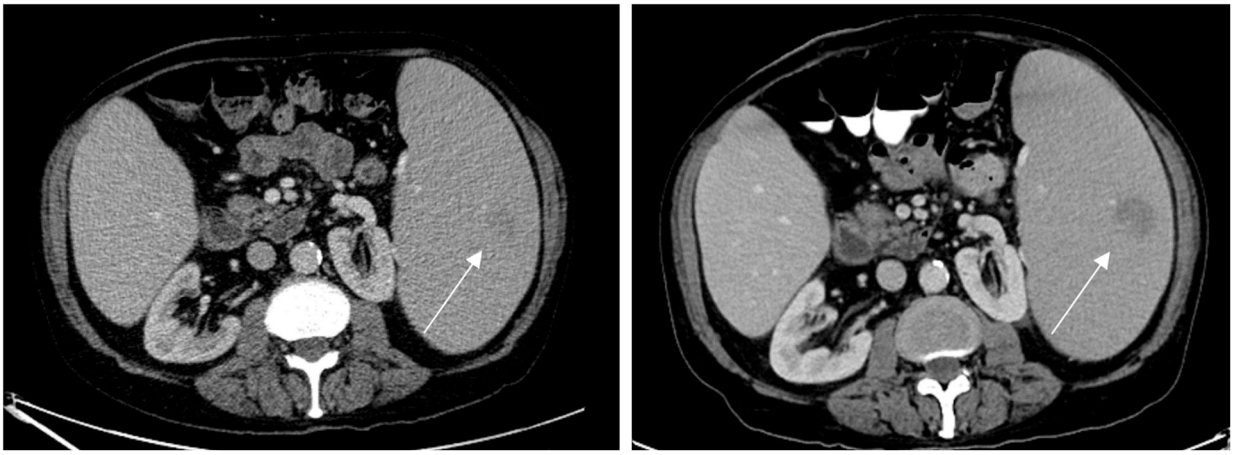

Figure 1.

74 year old male with bladder cancer and post-polycythemia vera myelofibrosis. Patient presented to an outside hospital with progressive anemia and subsequent diagnosis of acute myelogenous leukemia. Contrast-enhanced CT scans of the abdomen performed one day apart demonstrate a leukemic lesion (arrows) in the spleen, which was missed on the outside hospital scan (left image) ($CTDI_{vol}$ 9.4 mGy) and then identified on the follow up scan (Site 2 routine cancer protocol) at Site 2's tertiary cancer imaging center (right image) ($CTDI_{vol}$ 24.5 mGy).

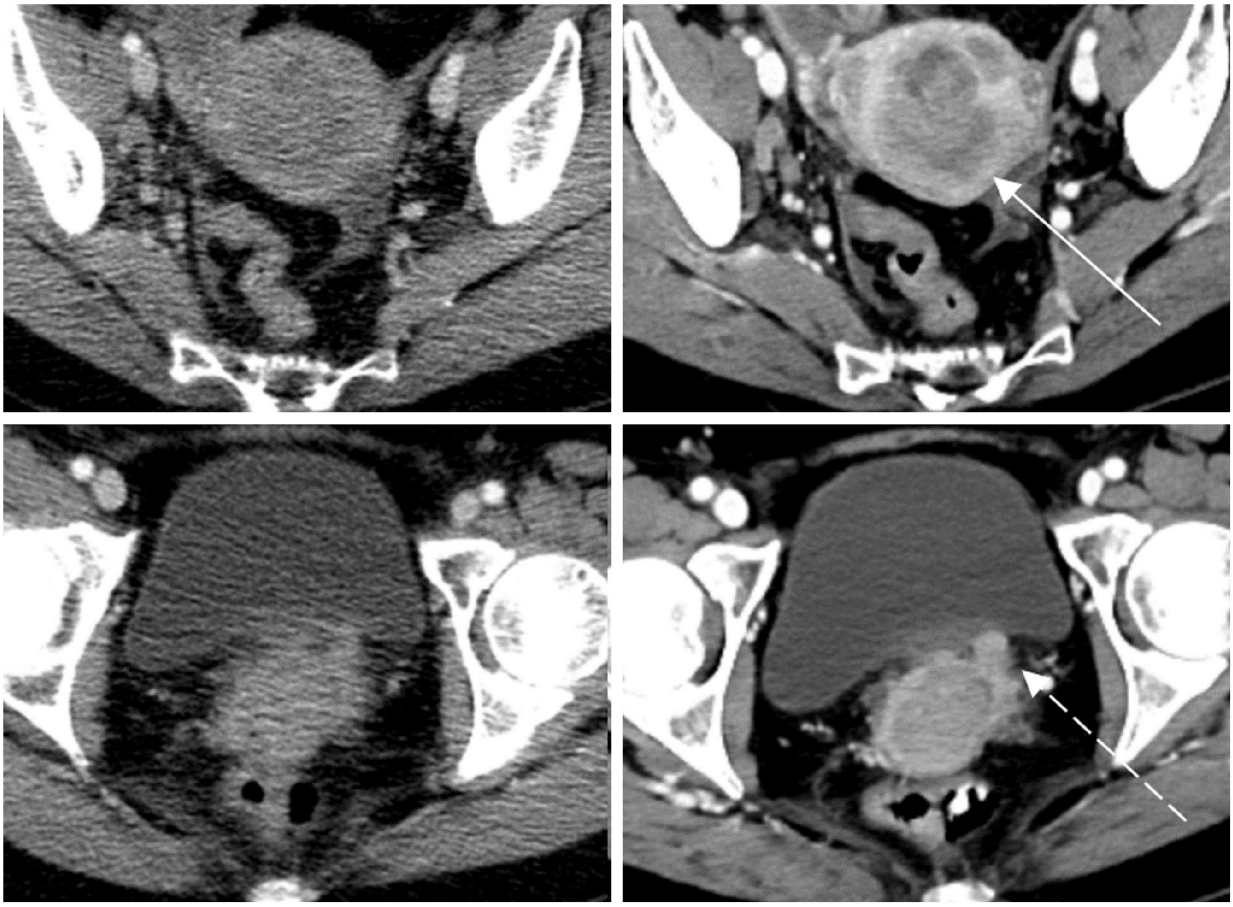

Figure 2.

62 year old female with acute abdominal pain, vaginal bleeding, and unintentional weight-loss. Contrast-enhanced CT scans of the abdomen performed 2 days apart revealed a vague uterine mass on outside hospital scans (left sided images) ($CTDI_{vol}$ 2.2 mGy). Site 2 routine protocol, tertiary hospital scan (right sided images)($CTDI_{vol}$ 14.7 mGy) delineated the myometrial invasion (arrow) and associated left ureterovesicular junction involvement (dashed arrow) with subsequent biopsy revealing uterine adenocarcinoma.

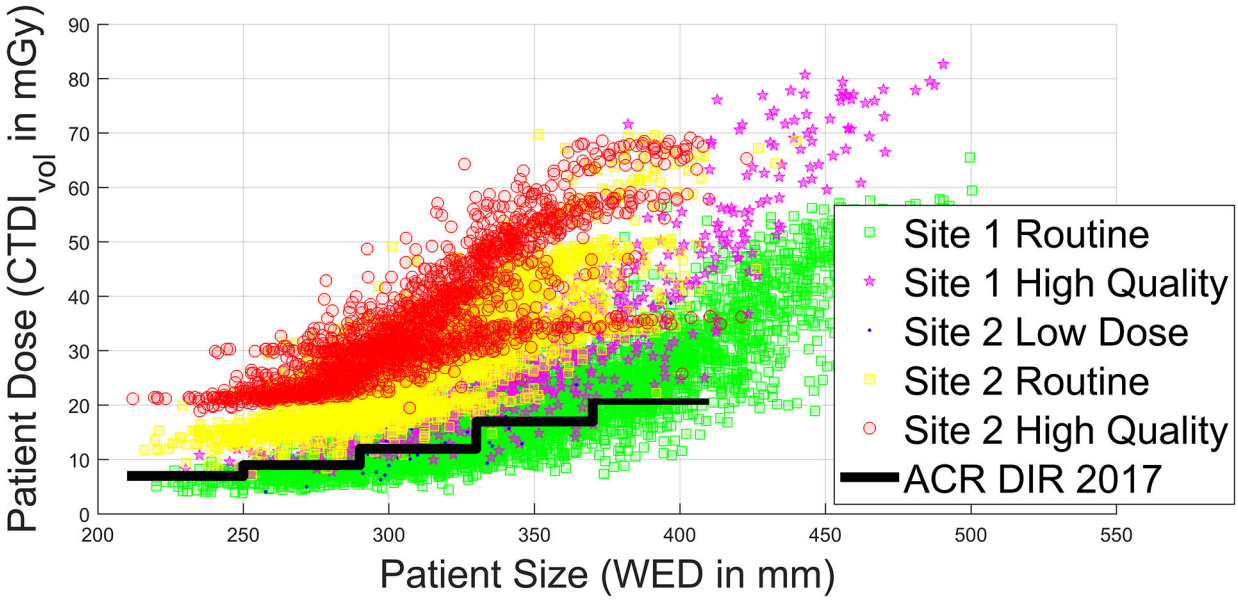

Figure 3.

Scatter plot of institutional data overlaid with ACR DIR 2017 dose data taken from Kanal *et al.* 2017[kanal]. The institutional protocols reflect abdominal protocols used for cancer imaging at Sites 1 and 2 (protocols described in Tables 1 and 2). The ACR "achievable dose" (i.e., 50th percentile) data is from abdomen pelvis exams with IV contrast, which inherently includes both general and oncologic exams.

Table 1.

Description of the indication to protocol mapping used at Sites 1 and 2.

Protocol Name	Protocolling/Indication information
Site 1 Routine	**Indication:** Evaluate for abdominal pathology other than hypervascular tumors. E.g., Abdominal pain (appendicitis, small bowel obstruction, diverticulitis, pancreatitis etc), source of infection (abscess/fluid collection). Used in follow up of lymphoma and testicular cancer. **Image Detection Tasks:** Identification of source of abdominal pain, infection, where need to visualize common sites like appendix, GB, diverticula, fluid collections, inflammatory changes, fairly high contrast tasks. For cancer follow up, may be surveilling in the setting of no evident disease or evaluating for more easily detected sites of disease (bone, nodal, spleen).
Site 1 High Image Quality	**Indications:** Higher image quality version of the routine abdomen pelvis protocol. This protocol is to be used for cancer follow-up on patients at risk for low contrast liver lesions/hepatic metastatic disease, which can be subtle. Typically, a determination would be made based on age and disease process (usually dependent on whether they could have metastatic disease to the liver). Used on Colorectal, Pancreas, Esophageal, Lung, Cholangiocarcinoma and Breast cancer. Not used on Lymphoma or Testicular cancer. Hypervascular metastatic disease (Renal cell, neuroendocrine tumor, hepatocellular carcinoma) imaged with protocol that includes late arterial phase, not this protocol. **Image Detection Tasks:** Visualization of solid organ lesions, often low contrast 10–20 HU difference between lesion and background liver and 4–5 mm object size is required. Visualization of texture within such lesions to enable lesion characterization is needed. Lesion margin visualization is important.
Site 2 Low Dose	**Indications:** Follow-up of treated leukemia/lymphoma and testicular cancer. Used on patients under 40 years of age. **Image Detection Tasks:** Monitoring for recurrence in patients with a low pretest probability of disease and/or in patients where recurrence is unlikely to be a low contrast task (i.e., low dose protocols typically assess for lymphadenopathy, splenomegaly, etc. rather than small, subtle liver lesions).
Site 2 Routine	**Indications:** Routine exams for most cancers in which multiphase evaluation is not required. **Image Detection Tasks:** Image quality meant to identify most oncologic disease presentations. Visualization of solid organ lesions, often low contrast 10–20 HU difference between lesion and background liver and sub 5 mm object size is required. Visualization of lesion texture may be needed.
Site 2 High Image Quality	**Indications:** Colorectal cancer, Non-contrast staging exams, Emergency/Inpatient exams. **Image Detection Tasks:** Enhanced image quality for a subset of patients (i.e., patients with potentially surgical liver lesions that may be subtle or oncology patients presenting with superimposed acute symptoms which often result in complex pathology also in need of restaging).

A brief description of the most challenging imaging detection task, required on an indication specific basis, is also listed in the table.

Table 2

Protocol technical scan parameters.

	Site 1 Routine (GE Revolution HD 750)	Site 1 High Image Quality (GE Revolution HD 750)	Site 2 Low Dose (GE Revolution HD 750)	Site 2 Routine (GE Revolution HD 750)	Site 2 High Image Quality (GE Revolution HD 750)
Beam Energy	Small: 100 kV Medium: 120 kV Large: 140 kV		All sizes: 120 kV		
AEC Control Parameter	Small:15.5 NI Medium: 18.5 NI Large: 23 NI	Small:11.5 NI Medium: 14 NI Large: 17 NI	Small:20 NI Medium: 25 NI Large: 29 NI	Small:11 NI Medium: 11 NI Large: 12 NI	Small: 9 NI Medium: 10 NI Large: 10 NI
Scan speed (rotation time/ collimation/ pitch)	Small:0.4s/40mm/ 0.984:1 Medium:0.6s/40mm/ 0.984:1 Large:0.8s/40mm/ 0.984:1	Small:0.4s/40mm/ 0.516:1 Medium:0.6s/40mm/ 0.516:1 Large:0.7s/40mm/ 0.516:1	0.5s/40mm/0.516:1	Small:0.5s/40mm/ 0.516:1 Medium:0.5s/40mm/ 0.516:1 Large:0.7s/40mm/ 0.516:1	Small:0.6s/40mm/ 0.516:1 Medium:0.6s/40mm/ 0.516:1 Large:0.7s/40mm/ 0.516:1
Slice thickness	Recon 1: 3.75×2.5 mm Recon 2: 1.25×0.625mm Reformats: SAG and COR 3×2 mm		Recon 1: 2.5×2.5 mm Recon 2: 2.5×2.5 mm Reformats: SAG and COR 2.5×2.5 mm	Recon 1: 5×5 mm Recon 2: 2.5×2.5 mm Reformats: SAG and COR 2.5×2.5 mm	
Recon options	Standard kernel, 40% ASiR, Plus Mode, (IQ enhance on thins)		Recon 1: Standard kernel, 70% ASiR-V, Plus Mode Recon 2: Standard + E1 kernel, 70% ASiR-V, Plus Mode	Recon 1: Standard, Plus Mode Recon 2: Standard + E1 kernel, Plus Mode Small: 30% ASiR-V Medium: 30% ASiR-V Large: 40% ASiR-V	

The parameters in this table reflect the highest volume scanner models at each site.

Table 3.

Median dose ($CTDI_{vol}$) values with their 95% confidence intervals at size ranges provided in the 2017 ACR DIR summary report (Kanal et al. 2017) 50th percentile dose for "Abdomen and Pelvis with contrast material".

Size* (WED) in mm	ACR DIR AD A/P w/IVC**	Site 1 Routine	Site 1 HIQ	Site 2 Low	Site 2 Routine	Site 2 HIQ
(210–250) 230	7	4.2 [3.7 4.7]	5.3 [3.5 7.1]	3.8 [−2.8 10.4]	11.0 [10.2 11.8]	15.7 [14.5 16.8]
(250–290) 270	9	7.7 [7.4 8.0]	10.7 [9.6 11.9]	7.2 [3.8 10.6]	17.7 [17.3 18.0]	24.8 [24.3 25.2]
(290–330) 310	12	12.2 [12.0 12.4]	17.9 [17.3 18.6]	12.6 [11.0 14.2]	26.1 [25.9 26.4]	34.9 [34.6 35.3]
(330–370) 350	17	18.3 [18.1 18.4]	27.5 [26.9 28.0]	21.1 [18.5 23.7]	36.8 [36.5 37.2]	46.1 [45.7 46.6]
(370–410) 390	21	26.2 [26.0 26.4]	40.2 [39.5 40.9]	34.7 [28.1 41.3]	50.4 [49.6 51.2]	58.6 [57.5 59.6]

*Size bin used have the ACR DIR ranges in parenthesis followed by the average of the bin range which was used to calculate doses for Sites 1 and 2.

**American College of Radiology Dose Index Registry Achievable Dose Abdomen and Pelvis with Contrast Material.

HIQ = high image quality, WED = water equivalent diameter

Table 4

Percentiles of Site 1 and Site 2 dose ($CTDI_{vol}$) data.

Percentile	ACR DIR AD A/P w/IVC**	Site 1 Routine	Site 1 HIQ	Site 2 Low	Site 2 Routine	Site 2 HIQ
5th	7	7.1	11.4	5.5	14.7	21.5
10th	9	8.4	13.1	7.2	15.6	22.3
25th	9	11.6	18.1	9.9	18.3	26.5
50th	12	17.5	25.9	12.9	25.5	31.9
75th	17	25.9	37.4	16.4	33.3	41.5
90th	17	36.8	55.6	24.7	42.1	53.4
95th	21	45.8	70.6	29.0	46.8	57.7

This table reports the range in patient dosing for each institution's protocols by percentile.

** American College of Radiology Dose Index Registry Achievable Dose Abdomen and Pelvis with Contrast Material.

HIQ = high image quality

Table 5.

p values from N-way anova accounting for location and patient size.

	Site 1 HIQ	Site 2 Low Dose	Site 2 Routine	Site 2 HIQ
Site 1 Routine	<0.001*	0.4234	<0.001*	<0.001*
Site 1 HIQ		<0.001*	<0.001*	<0.001*
Site 2 Low Dose			<0.001*	<0.001*
Site 2 Routine				<0.001*

p values are reported for location effect. The effect of patient size (WED) was always significant with a p-value <0.001 for all comparisons. HIQ = High Image Quality.