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Prioritizing Examination-Centered over Patient-Centered Dose Reduction: A Hazard of Institutional “Benchmarking”

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Abstract

Purpose—To evaluate whether examination-specific radiation dose metrics reliably measure an institution's success in reducing cancer risks.

Materials and Methods—We projected health benefits from dose-reduction programs in a hypothetical institution that sought to decrease exposures from abdominopelvic CT. Using modeling techniques to project radiation-induced cancer risks, and tertiary center data to inform the institution's abdominopelvic CT age distribution, we compared: a program in which effective doses were reduced equally (from 10 to 7-mSv) across all scans; to programs in which dose reduction was age-dependent. For each program, we projected lethal cancers averted, life expectancy gained, and average institutional dose achieved. Markov Chain Monte Carlo methods were used to estimate uncertainty in projections.

Results—The analysis' age distribution drew from 20,979 CT scans; 39% were from patients 65-years-old. To illustrate trends yielded, if all patients in the hypothetical institution received 7-mSv (instead of 10-mSv) scans, we projected the maximum number of lethal cancers averted to be 7/100,000 patients, and maximum life expectancy gained to be 0.26 days per patient, when averaged over the institution's population. When restricting dose reduction (from 10 to 7-mSv) to patients <65-years-old, benefits were slightly lower (5/100,000 patients, 0.22 days gained); however, the average institutional dose was substantially higher (8.2-mSv). While dose reduction in 65-year-old patients accounted for only 16% of possible institutional life expectancy gains, this patient group contributed disproportionately (39%) to the institution's average dose.

Conclusion—Institutional examination-specific dose metrics can be misleading, because the least benefited patients may contribute disproportionately towards “improved” averages.

INTRODUCTION

With heightened concerns about cancer risks from imaging, new emphasis has been placed upon tracking radiation doses at the institution level [1-6]. Automated technologies will soon allow most institutions to query their aggregate dose metrics in real time, allowing for rapid cross-institutional comparisons according to examination type, and facilitating data transfer to national registries and regulatory authorities [1-5]. The American College of Radiology Dose Index Registry represents one such data repository that is already in place [5, 7]. The generation of standardized, acceptable dose levels across imaging tests is a primary goal of this initiative, and is expected to prompt widespread convergence towards safer practices by encouraging changes at the institution level [5, 7].

As benchmarking procedures evolve, a clear benefit will initially dominate: a “top” level of diagnostically unnecessary exposure will rationally be eliminated from many examinations across participating institutions [8]. However, as the dose-reduction envelope is pushed further, it is important to consider a potential pitfall that can result. It is known that radiation-induced cancer risks depend on several patient factors, such as age, gender, and life expectancy [9-10]. This means that if, for a given examination type, a similar magnitude of dose reduction is applied to all patients – without attention to individual patient characteristics – some will benefit more than others. In particular, young patients without life-threatening diseases will, on average, benefit more than older patients with advanced or end-stage diseases [9-10]. If everyone benefits, though, why is this asymmetry a problem? Historically, many successful safety interventions have preferentially benefited specific patient groups – for example, handwashing guidelines preferentially benefit those most susceptible to nosocomial infections. Why is radiation dose reduction different?

The problem is that in many institutions, older patients, or patients with low life expectancies, account for a disproportionately large proportion of diagnostic radiation exposures [11]. This means that an institution's average reported dose level for a specific examination type (e.g. an abdominopelvic CT) – regardless of the specific metric used – will draw largely from patients who are the least likely to benefit from dose-reduction initiatives. When an aggregate quality metric draws substantially from a population that incurs the least associated benefit from the intervention, by definition, the value of the metric can be diminished. Moreover, depending on an institution's current practices, substantial dose reduction can result in appreciably poorer image quality. This sacrifice may be rational for younger, healthier patients who are at higher risk for radiation-induced cancers. However, in older, sicker patients, even small benefits imparted by superior image quality may outweigh benefits from dose reduction.

To evaluate implications of the above pitfall, we considered a hypothetical institution which sought to decrease their average effective dose for abdominopelvic CT. Using Markov modeling techniques to project radiation-induced cancer risks, combined with patient data from a tertiary medical center to inform the institution's age distribution for abdominopelvic CT, we compared the maximum possible health benefits gained by: (1) a program in which doses were reduced equally across all abdominopelvic CT scans; to (2) programs in which dose reduction was applied using age criteria. For each program, we calculated and

compared the average institutional effective dose achieved. Our purpose was to evaluate whether examination-specific radiation dose metrics are a reliable marker of an institution's success in reducing cancer risks.

MATERIALS AND METHODS

All patient data used in our analysis were collected under Institutional Review Board (IRB) approval and in compliance with HIPAA.

Study Overview

We projected the health benefits gained – and average effective dose levels achieved – for dose-reduction programs in a hypothetical institution that sought to decrease its average effective dose for abdominopelvic CT. We selected 10-mSv as the “starting” dose for all abdominopelvic CT scans; this is within the low range of recently reported effective dose levels for abdominopelvic CT [12-13]. Based on our institutional experience [BLINDED], and taking into account the rapid trajectory of dose-reduction technologies [15-17], 7-mSv was designated as the effective dose level for patients undergoing reduced-dose CT in our analysis. We first computed projections for a dose-reduction program in which patients of all ages received 7-mSv, instead of 10-mSv, CT scans. We then computed the same projections for a series of age-based dose-reduction programs, in which dose reduction (from 10 to 7-mSv) was only implemented in scans from patients below specified ages: <85; <75; <65; <55; <45; <35; <30 and <25-years-old.

Central to projections of institutional outcomes was the age distribution of patients who received abdominopelvic CT scans. We used data from our institution – a large, tertiary care center – to define the age distribution for the hypothetical institution in our analysis. To project health benefits for each dose-reduction program, we used a previously developed Markov model [14] that projected age and gender-specific radiation-induced cancer risks and life expectancy losses using an organ-based approach, and which was tailored to evaluate CT coverage of abdominopelvic anatomy. Combining our hypothetical framework, institutional age-distribution data, and radiation-risk model, we were able to generate concurrent projections of health benefits gained – and average effective dose levels achieved – across a spectrum of radiation dose-reduction programs.

Eliciting the Institutional Age Distribution for Abdominopelvic CT

We searched our institutional radiology information system database by examination date and code to identify abdominopelvic CT scans that met specific inclusion and exclusion criteria. Inclusion criteria were: 1) abdominopelvic CT with contrast performed at our institution; and 2) performance dates between January 1 and December 31, 2011. We excluded CT scans which, based on their code, were: 1) performed with a non-contrast phase; 2) CT vascular studies including CT angiography; 3) CT colonography; and 4) CT of either the abdomen or the pelvis (but not both). We also excluded CT scans if the patient was below 20 years of age at the time of the study. We instituted this lower age limit because many institutional dose-reduction initiatives already mandate patient-centered pediatric-specific practices.

If a patient had multiple CT scans within the year, each was analyzed as a separate patient encounter. This approach was valid because based upon linear no-threshold (LNT) radiation-risk model principles, each scan (whether from the same patient, or a different patient of the same age) should count equally towards the risk of developing lethal radiation-induced cancers when considering the institution's population as a whole [9]. Patient gender was recorded for each CT scan; all model projections incorporated the elicited gender distribution. Scan frequency was determined by decade for men and women, for the following age intervals, for use in subsequent analyses: 20-24; 25-29; 30-34; 35-44; 45-54; 55-64; 65-74; 75-84; 85 years or greater.

Modeling Health Benefits of Dose-Reduction Programs

Computing Life Expectancy Gains and Cancer Risks Averted at the Institution Level

As noted, we used a previously developed Markov model [14] to project lethal cancers averted (per 100,000 patients) and life expectancy gained, at the institutional level, by the implementation of each dose-reduction program. The Markov model was programmed in C++. The Markov model included two health states, “alive” and “dead,” a lifetime horizon, and a one-month cycle length. All patients began in the “alive” state, having undergone an abdominopelvic CT within the first month. Patients then could die from radiation-induced cancers or from all other causes as a function of their age and gender. Applying our institution's age distribution (for abdominopelvic CT) to the Markov model, we were able to compute cancer risks averted and life expectancy gained for each dose-reduction program evaluated in the hypothetical institution. Projections of health benefits were considered maximum estimates, because disease-specific causes of death which may have prompted imaging (e.g. metastatic colon cancer) were not incorporated, and would have resulted in lower projections [10].

Radiation-Risk Model for CT: Details of the Markov Model—The radiation-risk model [14] implements core elements of the Biological Effects of Ionizing Radiation (BEIR) VII report [9], a commonly used resource for projecting cancer risks from imaging. The model assumes a linear non-threshold risk-exposure relationship for all solid cancers, and a linear-quadratic relationship for leukemia [9]. Suggested methods of cancer risk transport from Japanese atomic bomb survivors and medically exposed cohorts to a current U.S. population were adopted [9].

An organ-based approach was used for risk estimation. Radiation-induced cancer mortality was modeled for 16 solid organs (lung, esophagus, stomach, pancreas, liver, colon, rectum, kidney, bladder, prostate, uterus, ovary, breast, central nervous system, thyroid, and oral cavity) and for leukemia, using organ-specific parameters from the BEIR VII report [9], Berrington de Gonzalez [18], and Preston [19]. For most organs, cancer mortality risks were computed as a geometric mean of excess relative risk (ERR) and excess absolute risk (EAR), using the Surveillance Epidemiology and End Results (SEER) cancer registry [20-22] to inform U.S. baseline cancer risks; this approach was substantiated by atomic bomb survivor data [9]. The BEIR VII models for breast and thyroid cancer were based on data from medically exposed cohorts in addition to atomic bomb survivors and deviated from the above approach. For projections of radiation-induced breast cancer, we adopted

methods from Preston and colleagues [19] which were used in the BEIR VII report [9]; only an EAR model was used in the case of breast cancer. For thyroid cancer, only an ERR model was used [9]. For cancers of the central nervous system, based on work by Berrington de Gonzalez and colleagues, we also used only an ERR model [18].

Our model was also tailored to reflect anatomic coverage typical for an abdominopelvic CT. As previously described, we used commercially available dosimetry software (ImPACT CT, London, England), simulation data derived from human phantom dosimetry studies, and tissue-weighting coefficients reported by the International Commission on Radiation Protection to identify a set of organ-specific equivalent doses that would correspond to 10-mSv and 7-mSv abdominopelvic CT effective dose levels [14, 23-24]. Organ-specific equivalent doses were then used to compute organ-specific radiation-induced cancer mortality risks.

Following CT, patients were continuously susceptible to death from solid cancers after 5 years, and leukemia after 2 years [9, 25]. As time passed in the model, by tracking radiation-induced cancer deaths for each dose-reduction program, we were able to compute corresponding projections of lethal cancers averted and life expectancy gained as a result of reductions in radiation exposure.

Markov Chain Monte Carlo (MCMC) Uncertainty Analysis

We used Markov Chain Monte Carlo (MCMC) methods to estimate the uncertainty of all analysis results [26]. Using MCMC methods, we randomly generated 1,000,000 unique parameter sets, each of which drew from distributions associated with several gender and organ-specific parameters in our radiation model [14]. Each of these 1,000,000 parameter sets can be interpreted to reflect a distinct propensity for radiation-induced carcinogenesis, e.g. defining uniquely the nature and extent of the exposure-risk relationship. To generate the uncertainty surrounding projections of health benefits in our analysis specific to each institutional program, we ran the radiation-risk model 1,000,000 times for each dose-reduction program, using each parameter set once. In this way, we were able to generate estimates (95% uncertainty intervals) that reflected the composite uncertainty of projections associated with each program considered.

Validation

To evaluate the generalizability of our results, we analogously projected health benefits achieved – for each dose-reduction program – using a nationally representative histogram of age and abdominopelvic CT frequency published by Mettler and colleagues [11]. We compared trends from institutional versus national results, to identify any meaningful differences.

RESULTS

Institutional Age and Frequency Distribution for Abdominopelvic CT

In total, 20,979 abdominopelvic CT scans were performed at our institution in 2011 that met our inclusion criteria ((51% (10,691/20,979) in women, and 49% (10,288/20,979) in men)

(Figure 1). Among these CT scans, 39% (8,162/20,979) were done for patients who were 65-years-old, while 61% (12,817/20,979) were done for patients who were 20-64 years of age.

Dose-Reduction Programs, Cancer Risks, and Institutional Dose Averages

Table 1 includes, for each dose-reduction strategy evaluated: the average institutional effective dose level achieved; the percentage of CT scans performed with dose reduction (e.g. from 10-mSv to 7-mSv); the projected number of lethal cancers averted (per 100,000 patients scanned) in the institution's population; and the average life expectancy gained by dose reduction per patient, when averaged over the institution's population.

If all institutional patients undergoing abdominopelvic CT – regardless of age – underwent dose reduction from 10-mSv to 7-mSv, we projected the maximum possible lethal cancers averted to be 7/100,000, corresponding to a maximum possible life expectancy gain of 0.26 days per patient for the institution's population. When dose reduction was restricted to the 39% of patients that were <65-years-old, lethal cancers averted dropped to 5/100,000, and life expectancy gains dropped to 0.22 days, representing a 16% decrease in institutional life expectancy gains. However, because patients 65-years-old contributed substantially to the institution's average effective dose, a dose-reduction program that was restricted to patients <65-years-old yielded a substantially higher average effective dose of 8.2-mSv as compared to 7-mSv.

Trends were more pronounced when dose-reduction programs were restricted to patients under 75 or 85 years of age (Table 1). For example, compared to a program in which all patients received dose reduction (from 10 to 7-mSv), using a 75-year-old threshold, the number of lethal cancers averted dropped from 7 to 6.5/100,000, and life expectancy gains from 0.26 to 0.25 days. The corresponding average institutional dose again increased substantially, from 7 to 7.5-mSv.

Figure 2a graphically depicts the correlation between health benefits achieved and average institutional effective dose yielded for each dose-reduction program considered. As increasingly elderly patients underwent reduced-dose CT, projected life expectancy gains in the institution's population demonstrated a “diminishing returns” curvature. However, because older patients contributed substantially to the population of patients undergoing abdominopelvic CT, and therefore to the institution's average effective dose, even when only the most elderly were spared of dose reduction, the institution's average effective dose was substantially higher relative to a program in which all patients underwent dose reduction.

Validation

Using published data to obtain the age-frequency distribution of abdominopelvic CT at the national level [11], we analogously depicted the correlation between health benefits achieved and average institutional effective dose yielded for each dose-reduction program (Figure 2b). In this validation source, 36.2% of CT cases were performed in patients 65 and older [11]. Result trends were similar, with no meaningful differences observed when comparing single-institution versus national age-distribution data.

DISCUSSION

Our findings demonstrate a pitfall that can occur when institutions are focused upon lowering examination-specific radiation dose metrics at the institution level – namely, the potential to compromise patient-centered practices. Two circumstances drive this pitfall: first, the dependency of radiation-induced cancer risks upon patient factors such as age and life expectancy [9]; and second, the reality that older patients with low life expectancy oftentimes constitute a large proportion of patients imaged [11]. While patients 65-years-old account for 39% of abdominopelvic CT scans done in our institution, health benefits achieved by dose reduction in this subpopulation are relatively lower. However, excluding these patients from dose-reduction efforts, even if the clinical risk-benefit ratio is unlikely to warrant dose reduction, would result in a substantial increase in the institution's average effective dose for abdominopelvic CT. Put another way, tailoring dose-reduction efforts to preferentially affect younger, healthier patients – allowing elderly patients or patients with low life expectancy the benefits in image quality that may be afforded by higher radiation doses – may compromise an institution's performance metrics, even though their efforts may be appropriately patient-centered. Our findings emphasize the need to consider more granular, patient-centered benchmarks when evaluating an institution's performance in radiation dose reduction.

The illustrated pitfall is not intended to undermine the importance of the American College of Radiology Dose Index Registry or of diagnostic reference levels, such as described in the Image Wisely® campaign, which represent a widely accepted strategy and have been shown to reduce inter-institutional variability in radiation doses [8]. For many institutions still engaged in implementing basic dose-reduction methodologies, initial dose reduction may be achieved without reduction in diagnostic quality. In this way, benchmarking will remain an important and valuable tool to incentivize further dose-reduction efforts. However, as institutions engage in more aggressive dose reduction practices, there is a risk of appreciably poorer image quality and reduced diagnostic value [27-28]. In these situations, it is critical to consider the differential benefit received by individual patient populations.

Our analysis considers only age-based criteria for dose reduction. However, several other patient factors may also affect radiation-induced cancer risks and dose-reduction metrics; these merit consideration when planning dose-reduction initiatives [5, 8-10]. Life expectancy, independent of age, also affects radiation-induced cancer risks in two ways [10]. First, with substantial competing risks of death, radiation-induced cancer risks are lower [10]. Second, because of expected latency periods between radiation exposure and cancer development, patients with very low life expectancy may incur no radiation-induced cancer risks from imaging [9, 25]. Patient habitus and geometry are also linked to cancer risks [3, 5]. For example, patients with obesity may require higher doses to achieve comparable image quality. In these patients, higher doses may be more appropriate from a risk-benefit standpoint. Patient gender also affects radiation-induced cancer risks, with women, in general, experiencing relatively higher cancer risks (per identical exposure) compared to men [9].

We used our institution's age distribution for abdominopelvic CT in this study. However, institution-level projections ultimately depend upon the institution's case mix. If we had drawn our age distribution from an institution with a greater proportion of young people receiving abdominopelvic CT, our results would have differed. In particular, dose reduction for patients 65-years-old may have resulted in less health benefits gained at the institution level, but would have produced a more modest decrease in the institution's average effective dose. The heterogeneous case mix of patients scanned in different settings – for example, hospitals specializing in cancer care, women's health, or rehabilitation – must be considered carefully when measuring institutional performance, so as not to disadvantage institutions with unique case mixes that are attending to patient-specific factors during protocol development.

Nonetheless, our finding that a high prevalence of patients undergoing abdominopelvic CT are 65-years-old was supported by our validation source – a nationally representative cohort – in which 36.2% of patients undergoing abdominopelvic CT were 65-years-old [11]. In addition, Smith-Bindman and colleagues, in a recent observational study of radiation exposure in an integrated healthcare system, found that among patients receiving the highest cumulative radiation doses (>50 -mSv/year) in 2010, 44% (5,824/13,216) were 65-years-old in age [29]. Additional observational studies have also indicated a correlation between lower life expectancy and increased CT scanning [30-32]. Zondervan and colleagues [31], in a study describing CT utilization in patients 18-35 years of age in a large academic center, found that over a mean follow-up period of approximately five years, 46% (32/70) of patients who underwent CT more than 15 times in a 4-year period died. Sodickson and colleagues, in a similarly large academic center, found that among 2,298 patients with the highest lifetime level of cumulative risk associated with CT, 85% had a cancer diagnosis [30]. Together, these studies underscore several patient groups who would receive differentially lower benefits from dose-reduction initiatives compared to younger or healthier populations.

Our study has additional limitations that merit consideration. First, we modeled hypothetical, idealized dose-reduction scenarios and targets. Due to differences in patient size and geometry, and in scanner capabilities, it is not possible – nor would it be desirable – to achieve the same effective dose for every CT scan. Superimposed upon variability in patient and scanner factors is uncertainty associated with dose estimation methods [33]. The “effective dose” metric has known limitations [34-37], one of which pertains to the assumption of uniform patient geometry and size [35]. Despite the above considerations, the trends and pitfall that we demonstrate would not change. Our approach allowed us to concurrently explore the effects of numerous dose-reduction programs in ways that would not be feasible in real patient care settings.

Second, we used Markov modeling techniques in order to project radiation-induced cancer risks at the population level. Simplifying assumptions are an inherent characteristic of any mathematical model which attempts to replicate disease processes. Within the model, we used BEIR VII assumptions – including a linear no-threshold relationship between radiation exposure and cancer risks – when modeling radiation-induced cancer risks [9]. BEIR VII outcomes extrapolations, which draw from a large Japanese atomic bomb survivor cohort,

remain unproven in a diagnostic imaging setting [9, 38]. However, there is growing evidence to support an exposure-risk relationship in diagnostic imaging [39-40], and the BEIR VII report remains the most widely accepted resource for projecting radiation-induced cancer risks from diagnostic imaging [9, 41-42].

Recent work by Shuryak and colleagues raises the possibility that the BEIR VII model may underestimate the true risk associated with radiation in older patients [43]. This is a preliminary analysis, and more work must be done to confirm these findings before practice guidelines can be based on them. However, it should be emphasized that patient age is used in this analysis for demonstration purposes; the same principle applies to other patient factors that affect radiation risk, such as life expectancy.

Third, a primary rationale for avoiding extreme dose-reduction efforts is that the added radiation produces superior image quality. While the diagnostic acceptability of dose reduction has been reported in some clinical settings [44-47], the adverse health outcomes that could result – due to lowered rates of disease detection or exclusion – have not been evaluated to the extent that would be necessary for reliable risk-benefit comparisons. This is due to the inherent challenge of developing effective study designs for this purpose. For example, we projected that a 3-mSv dose reduction could result in up to 7 lethal cancers averted in 100,000 patients scanned – in most clinical scenarios, the resources required to power a study that could demonstrate whether this magnitude of benefit outweighed risks resulting from lower image quality would be preclusive. As a result, opinion-based consensus will be necessary to develop guidelines and criteria for patient-centered dosimetry. Singh and colleagues [48] successfully implemented a patient-centered dosimetry algorithm, sensitive to patient size and clinical indication, for pediatric patients undergoing CT at a large academic center. Notably, where dose-optimization initiatives have not yet been started, initial dose reductions may not impact imaging quality in a discernible way [17, 45-46].

Fourth, in our modeling analysis, we used a CT age distribution that was constructed on a per-scan, rather than a per-patient, basis. Cumulative risks for patients scanned multiple times – for example, young patients with inflammatory bowel disease – and the effects of dose-reduction in these populations, were not specifically addressed. However, applying the linear no-threshold model, previously incurred (or future expected) risks should not influence risks from other exposures in a patient's life; each exposure-risk “event” is independent [9, 49-53]. Following this logic, institutional CT dosimetry decisions should not differentiate between patients who have – or will be – scanned multiple times in their lives and those who have not, unless differences are related to anticipated benefits rather than risks.

In conclusion, if institutions engage in aggressive one-size-fits-all dose-reduction strategies, the safety goal of cross-institutional and national comparisons may be undermined. In particular, the least benefited patients may contribute disproportionately towards “improved” averages. Notably, the challenge of implementing patient-centered practices is substantial. The identification of patient-centered dose-reduction criteria and algorithms, at the institution level, will require additional research and consensus review to determine the

ideal balance between granularity and feasibility. Nevertheless, patient-centered practices must become a priority within the imaging community in the coming years – attention to basic patient characteristics that govern radiation-induced cancer risks is essential for providing the best possible care.

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REFERENCES

1. Cook TS, Zimmerman SL, Steingall SR, Maidment AD, Kim W, Boonn WW. Informatics in Radiology: RADIANCE: An Automated, Enterprise-wide Solution for Archiving and Reporting CT Radiation Dose Estimates. *Radiographics*. 2011; 31:1833–46. [PubMed: 21969661]
2. Ikuta I, Sodickson A, Wasser EJ, Warden GI, Gerbaudo VH, Khorasani R. Exposing Exposure: Enhancing Patient Safety through Automated Data Mining of Nuclear Medicine Reports for Quality Assurance and Organ Dose Monitoring. *Radiology*. 2012; 264:406–413. [PubMed: 22627599]
3. Sodickson A, Warden GI, Farkas CE, et al. Exposing Exposure: Automated Anatomy-specific CT Radiation Exposure Extraction for Quality Assurance and Radiation Monitoring. *Radiology*. 2012; 264:397–405. [PubMed: 22668563]
4. Wang S, Pavlicek W, Roberts CC, et al. An automated DICOM database capable of arbitrary data mining (including radiation dose indicators) for quality monitoring. *J Digit Imaging*. 2011; 24:223–233. [PubMed: 20824303]
5. McCollough CH. Automated data mining of exposure information for dose management and patient safety initiatives in medical imaging. *Radiology*. 2012; 264:322–324. [PubMed: 22821691]
6. Brenner DJ, Hall EJ. Computed tomography--an increasing source of radiation exposure. *N Engl J Med*. 2007; 357:2277–2284. [PubMed: 18046031]
7. [10/9/12] American College of Radiology Dose Index Registry Homepage. <https://nrdcr.acr.org/Portal/DIR/Main/page.aspx>.
8. McCollough, CH. [10/9/12] Diagnostic Reference Levels. <http://www.imagewisely.org/~media/ImageWisely%20Files/Medical%20Physicist%20Articles/TW%20McCullough%20Diagnostic%20Reference%20Levels.pdf>.
9. National Research Council (U.S.). Health Risks from Exposure to Low Levels of Ionizing Radiation, BEIR VII Phase 2. National Academy of Sciences; Washington, D.C.: 2006. Advisory Committee on the Biological Effects of Ionizing Radiations..
10. Brenner DJ, Shuryak I, Einstein AJ. Impact of reduced patient life expectancy on potential cancer risks from radiologic imaging. *Radiology*. 2011; 261:193–198. [PubMed: 21771956]
11. Mettler FA Jr, Thomadsen BR, Bhargavan M, et al. Medical radiation exposure in the U.S. in 2006: preliminary results. *Health Phys* 2008. 95:502–507.
12. Smith-Bindman R, Lipson J, Marcus R, et al. Radiation dose associated with common computed tomography examinations and the associated lifetime attributable risk of cancer. *Arch Intern Med*. 2009; 169:2078–2086. [PubMed: 20008690]
13. Nationwide Evaluation of X-Ray Trends (NEXT), Tabulation and Graphical Summary of 2000 Survey of Computed Tomography.. Conference of Radiation Control Program Directors, Inc. and Food and Drug Administration; http://www.crcpd.org/Pubs/NEXT_docs/NEXT2000-CT.pdf.
14. Pandharipande PV, Eisenberg JD, Lee RJ, et al. Patients with testicular cancer undergoing CT surveillance demonstrate a pitfall of radiation-induced cancer risk estimates: the timing paradox. *Radiology*. 2013; 266:896–904. [PubMed: 23249573]

15. Singh S, Kalra MK, Hsieh J, et al. Abdominal CT: comparison of adaptive statistical iterative and filtered back projection reconstruction techniques. *Radiology*. 2010; 257:373–383. [PubMed: 20829535]
16. Singh S, Kalra MK, Thrall JH, Mahesh M. CT radiation dose reduction by modifying primary factors. *J Am Coll Radiol*. 2011; 8:369–372. [PubMed: 21531317]
17. McCollough CH, Chen GH, Kalender W, et al. Achieving routine submillisievert CT scanning: report from the summit on management of radiation dose in CT. *Radiology*. 2012; 264:567–580. [PubMed: 22692035]
18. Berrington de Gonzalez A, Mahesh M, Kim KP, et al. Projected cancer risks from computed tomographic scans performed in the United States in 2007. *Arch Intern Med* 2009. 169:2071–2077.
19. Preston DL, Mattsson A, Holmberg E, Shore R, Hildreth NG, Boice JD Jr. Radiation effects on breast cancer risk: a pooled analysis of eight cohorts. *Radiat Res*. 2002; 158:220–235. [PubMed: 12105993]
20. Horner, MJ.; Ries, LAG.; Krapcho, M.; Neyman, N.; Aminou, R.; Howlander, N.; Altekruse, SF.; Feuer, EJ.; Huang, L.; Mariotto, A.; Miller, BA.; Lewis, DR.; Eisner, MP.; Stinchcomb, DG.; Edwards, BK., editors. SEER Cancer Statistics Review, 1975-2006. National Cancer Institute; Bethesda, MD: 2009. http://seer.cancer.gov/csr/1975_2006/, based on November 2008 SEER data submission, posted to the SEER web site
21. Surveillance Epidemiology and End Results (SEER) Program (www.seer.cancer.gov) SEER*Stat Database: Incidence - SEER 17 Regs Research Data + Hurricane Katrina Impacted Louisiana Cases, Nov 2009 Sub (2000-2007) <Katrina/Rita Population Adjustment> - Linked To County Attributes - Total U.S., 1969-2007 Counties, National Cancer Institute, DCCPS, Surveillance Research Program, Cancer Statistics Branch, released April 2010, based on the November 2009 submission.
22. Surveillance Epidemiology and End Results (SEER) Program (www.seer.cancer.gov) SEER*Stat Database: Mortality - All COD, Aggregated With State, Total U.S. (1969-2006) <Katrina/Rita Population Adjustment>, National Cancer Institute, DCCPS, Surveillance Research Program, Cancer Statistics Branch, released May 2009. Underlying mortality data provided by NCHS (www.cdc.gov/nchs).
23. International Commission on Radiological Protection. 1990 recommendations of the International Commission on Radiological Protection: user's edition. 1st ed.. Published for the International Commission on Radiological Protection by Pergamon Press; Oxford; New York: 1992.
24. Jones, DG.; Shrimpton, PC. [10/27/12] NRPB-SR250: Normalized organ doses for x-ray computed tomography calculated using Monte Carlo techniques, Health Protection Agency, UK. http://www.hpa.org.uk/webw/HPAweb&HPAwebStandard/HPAweb_C/1195733753330?p=1153846674387#r250.
25. Office of Radiation and Indoor Air. Modifying EPA Radiation Risk Models Based on BEIR VII draft white paper: U.S. Environmental Protection Agency. 2006
26. Spall, J. Introduction to Stochastic Search and Optimization. Wiley Interscience; Hoboken, NJ: 2003.
27. Cohen MD. CT radiation dose reduction: can we do harm by doing good? *Pediatr Radiol*. 2012; 42:397–398. [PubMed: 22302318]
28. Leng S, Yu L, McCollough CH. Radiation dose reduction at CT enterography: How low can we go while preserving diagnostic accuracy? *AJR Am J Roentgenol*. 2010; 195:76–77. [PubMed: 20566799]
29. Smith-Bindman R, Miglioretti DL, Johnson E, et al. Use of diagnostic imaging studies and associated radiation exposure for patients enrolled in large integrated health care systems, 1996-2010. *JAMA*. 2012; 307:2400–2409. [PubMed: 22692172]
30. Sodickson A, Baeyens PF, Andriole KP, et al. Recurrent CT, cumulative radiation exposure, and associated radiation-induced cancer risks from CT of adults. *Radiology*. 2009; 251:175–184. [PubMed: 19332852]

31. Zondervan RL, Hahn PF, Sadow CA, Liu B, Lee SI. Frequent body CT scanning of young adults: indications, outcomes, and risk for radiation-induced cancer. *J Am Coll Radiol*. 2011; 8:501–507. [PubMed: 21723488]
32. Zondervan RL, Hahn PF, Sadow CA, Liu B, Lee SI. Body CT Scanning in Young Adults: Examination Indications, Patient Outcomes, and Risk of Radiation-induced Cancer. *Radiology*. 2013; 267:460–469. [PubMed: 23386731]
33. McCollough CH. Patient dose in cardiac computed tomography. *Herz*. 2003; 28:1–6. [PubMed: 12616315]
34. Brenner DJ. Effective dose: a flawed concept that could and should be replaced. *British Journal of Radiology*. 2008; 81:521–523. [PubMed: 18443016]
35. McCollough CH, Christner JA, Kofler JM. How Effective Is Effective Dose as a Predictor of Radiation Risk? *American Journal of Roentgenology*. 2010; 194:890–896. [PubMed: 20308487]
36. Bankier AA, Kressel HY. Through the Looking Glass Revisited: The Need for More Meaning and Less Drama in the Reporting of Dose and Dose Reduction in CT. *Radiology*. 2012; 265:4–8. [PubMed: 22993216]
37. Martin CJ. Effective dose: how should it be applied to medical exposures? *Br J Radiol*. 2007; 80:639–647. [PubMed: 17646189]
38. Hendee WR, O'Connor MK. Radiation risks of medical imaging: separating fact from fantasy. *Radiology*. 2012; 264:312–321. [PubMed: 22821690]
39. Brenner DJ, Hall EJ. Cancer Risks from CT Scans: Now We Have Data, What Next? *Radiology*. 2012; 265:330–331. [PubMed: 22915598]
40. Pearce MS, Salotti JA, Little MP, et al. Radiation exposure from CT scans in childhood and subsequent risk of leukaemia and brain tumours: a retrospective cohort study. *Lancet*. 2012; 380:499–505. [PubMed: 22681860]
41. Little MP, Wakeford R, Tawn EJ, Bouffler SD, Berrington de Gonzalez A. Risks associated with low doses and low dose rates of ionizing radiation: why linearity may be (almost) the best we can do. *Radiology*. 2009; 251:6–12. [PubMed: 19332841]
42. Kong CY, Lee JM, McMahon PM, et al. Using radiation risk models in cancer screening simulations: important assumptions and effects on outcome projections. *Radiology*. 2012; 262:977–984. [PubMed: 22357897]
43. Shuryak I, Sachs RK, Brenner DJ. Cancer Risks After Radiation Exposure in Middle Age. *JNCI Journal of the National Cancer Institute*. 2010; 102:1628–1636.
44. Kim K, Kim YH, Kim SY, et al. Low-dose abdominal CT for evaluating suspected appendicitis. *N Engl J Med*. 2012; 366:1596–1605. [PubMed: 22533576]
45. Singh S, Kalra MK, Do S, et al. Comparison of hybrid and pure iterative reconstruction techniques with conventional filtered back projection: dose reduction potential in the abdomen. *J Comput Assist Tomogr*. 2012; 36:347–353. [PubMed: 22592622]
46. Singh S, Kalra MK, Shenoy-Bhangle AS, et al. Radiation dose reduction with hybrid iterative reconstruction for pediatric CT. *Radiology*. 2012; 263:537–546. [PubMed: 22517962]
47. Fletcher JG, Grant KL, Fidler JL, et al. Validation of Dual-Source Single-Tube Reconstruction as a Method to Obtain Half-Dose Images to Evaluate Radiation Dose and Noise Reduction: Phantom and Human Assessment Using CT Colonography and Sinogram-Affirmed Iterative Reconstruction (SAFIRE). *J Comput Assist Tomogr*. 2012; 36:560–569. [PubMed: 22992607]
48. Singh S, Kalra MK, Moore MA, et al. Dose reduction and compliance with pediatric CT protocols adapted to patient size, clinical indication, and number of prior studies. *Radiology*. 2009; 252:200–208. [PubMed: 19435938]
49. Durand DJ. A rational approach to the clinical use of cumulative effective dose estimates. *AJR*. 2011; 197:160–162. [PubMed: 21701025]
50. Durand DJ, Dixon RL, Morin RL. Utilization strategies for cumulative dose estimates: a review and rational assessment. *J Am Coll Radiol*. 2012; 9:480–485. [PubMed: 22748788]
51. BLINDED.
52. Eisenberg JD, Harvey HB, Moore DA, Gazelle GS, Pandharipande PV. Falling prey to the sunk cost bias: a potential harm of patient radiation dose histories. *Radiology*. 2012; 263:626–628. [PubMed: 22623688]

53. Pandharipande PV, Eisenberg JD, Avery LL, et al. JOURNAL CLUB: How Radiation Exposure Histories Influence Physician Imaging Decisions: A Multicenter Radiologist Survey Study. *AJR*. 2013; 200:1275–1283. [PubMed: 23701064]

Figure 1. Age distribution for abdominopelvic CT in a large tertiary care center. In 2011, 20,979 abdominopelvic CT scans (with intravenous contrast) were performed for patients 20 years or older

A large proportion 39% (8,162/20,979) were performed in patients who were 65-years-old or greater. These empiric data informed the CT age distribution for the hypothetical institution in our analysis.

a.

b.

Figure 2. Health benefits gained versus average effective dose level achieved in a hypothetical institution using an age-based approach to abdominopelvic CT radiation dose reduction, plotted using two different CT age distributions

Projections and 95% uncertainty intervals were plotted using two different age distributions for abdominopelvic CT: one based on our institutional experience (**Figure 2a**); and another elicited from published national data for validation purposes [11] (**Figure 2b**). Dose reduction was defined to be from 10-mSv to 7-mSv. As increasingly elderly patients received dose reduction, projected life expectancy gains demonstrated a “diminishing returns” curvature (blue line). However, because older patients contributed substantially to the population of patients undergoing abdominopelvic CT, sparing even only the most elderly patients of dose reduction led to substantial increases in average institutional effective dose levels (red line). Projections based on single-institution versus national age distributions were not meaningfully different.

Table 1
Health Benefits Gained and Average Institutional Effective Dose Achieved for Each Age-Based Dose-Reduction Program

Dose Reduction Program for Abdominopelvic CT [*]	Average Institutional Effective Dose (mSv)	% Scans Performed with Dose Reduction	Average Lethal Cancers Averted (Per 100,000 Patients)	Average Life Expectancy Gained by Dose Reduction (Days Per Patient)	% Life Expectancy Saved [†]
7mSv CT in all patients	7	100	7 ± 2.8 [‡]	0.260 ± 0.102 [‡]	100
Dose reduction restricted to <85yo	7.1	96.2	7 ± 2.8	0.259 ± 0.102	99.9 ± 0.0 [‡]
Dose reduction restricted to <75yo	7.5	83.5	6.5 ± 2.6	0.252 ± 0.099	97.1 ± 0.4
Dose reduction restricted to <65yo	8.2	61.1	5.2 ± 2.1	0.218 ± 0.086	83.9 ± 1.3
Dose reduction restricted to <55yo	8.9	37	3.4 ± 1.4	0.156 ± 0.062	59.9 ± 1.8
Dose reduction restricted to <45yo	9.4	18.8	1.8 ± 0.7	0.090 ± 0.036	34.7 ± 1.5
Dose reduction restricted to <35yo	9.7	9.1	0.9 ± 0.4	0.048 ± 0.019	18.5 ± 0.9
Dose reduction restricted to <30yo	9.8	5.6	0.6 ± 0.2	0.032 ± 0.013	12.2 ± 0.6
Dose reduction restricted to <25yo	9.9	2.4	0.3 ± 0.1	0.015 ± 0.006	5.8 ± 0.3
10-mSv CT in all patients	10	0	0	0	0

^{*} For each program, dose reduction was defined as decreasing the effective dose for abdominopelvic CT from 10-mSv to 7-mSv. Patients not receiving dose reduction were assumed to undergo 10-mSv abdominopelvic CT scans.

[†] Percentage life expectancy saved was calculated as a proportion of the total possible life expectancy saved (0.260 days) if all patients underwent dose reduction from 10 to 7-mSv, regardless of age.

[‡] All projections are presented with 95% uncertainty intervals.