Expanding the Concept of Diagnostic Reference Levels to Noise and Dose Reference Levels in CT

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OBJECTIVE. Diagnostic reference levels were developed as guidance for radiation dose in medical imaging and, by inference, diagnostic quality. The objective of this work was to expand the concept of diagnostic reference levels to explicitly include noise of CT examinations to simultaneously target both dose and quality through corresponding reference values.

MATERIALS AND METHODS. The study consisted of 2851 adult CT examinations performed with scanners from two manufacturers and two clinical protocols: abdominopelvic CT with IV contrast administration and chest CT without IV contrast administration. An institutional informatics system was used to automatically extract protocol type, patient diameter, volume CT dose index, and noise magnitude from images. The data were divided into five reference patient size ranges. Noise reference level, noise reference range, dose reference level, and dose reference range were defined for each size range.

RESULTS. The data exhibited strong dependence between dose and patient size, weak dependence between noise and patient size, and different trends for different manufacturers with differing strategies for tube current modulation. The results suggest size-based reference intervals and levels for noise and dose (e.g., noise reference level and noise reference range of 11.5–12.9 HU and 11.0–14.0 HU for chest CT and 10.1–12.1 HU and 9.4–13.7 HU for abdominopelvic CT examinations) that can be targeted to improve clinical performance consistency.

CONCLUSION. New reference levels and ranges, which simultaneously consider image noise and radiation dose information across wide patient populations, were defined and determined for two clinical protocols. The methods of new quantitative constraints may provide unique and useful information about the goal of managing the variability of image quality and dose in clinical CT examinations.

Keywords: CT performance, diagnostic reference levels, image noise, patient population, radiation dose

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CT procedures should be designed, evaluated, and ideally optimized on the basis of their benefit-to-risk ratio. This means that a procedure should be optimized such that radiation exposure is as low as reasonably achievable (ALARA) while acquisition of acceptable clinical images is ensured [1, 2]. Toward that goal, the International Commission on Radiological Protection (ICRP) and the International Atomic Energy Agency have suggested that diagnostic reference levels (DRLs) be used as a practical tool to promote optimization in multiple ways [3, 4]. The ICRP highlights the value of DRL quantity as a radiation metric for assessing the amount of ionizing radiation used to perform a medical imaging examination, DRL value as the 75th percentile value of the distribution of the medians of the distributions of the DRL quantity obtained from surveys, and DRL process as the cyclic process of establishing DRL values as a tool for optimization. Regarding quantities for DRLs, volume CT dose index ($CTDI_{vol}$), dose-length product, organ dose, and effective dose are among the metrics currently in use [5].

Despite the valuable role of DRL in managing radiation dose, the International Atomic Energy Agency has equally recognized that dose is only "one of the steps in the overall process of optimization" [4]. To embody the essence of diagnostic in DRL and reasonably achievable in ALARA, DRLs should be expanded to include diagnostic image quality [3]. DRL metrology, which currently does not include image quality, is based on dose metrics per procedure. To expand the DRL

TABLE 1: Summary of Examinations Included in Study

CT Scanner	No. of Examinations	Slice Thickness (mm)	Detector Configuration (mm)	Tube Voltage (kV)	Angular Automatic Tube Current Modulation
Abdominopelvic CT protocol with contrast administration					
A	347	2.5	40	120, 140	28.0 (NI)
B	714	3.0–5.0	38.4	100, 120, 140	261 (Q)
Chest CT protocol without contrast administration					
A	1179	2.5–5.0	40	120, 140	19.2 (NI)
B	611	3.0–5.0	38.4	120, 140	150 (Q)

Note—Scanner A was a Discovery CT750HD (GE Healthcare), and scanner B was a Somatom Defintion Flash (Siemens Healthineers). NI = noise index, Q = reference effective tube current–time product (mAs).

TABLE 2: Summary of Patient Age, Effective Diameter, Noise, and Volume CT Dose Index ($CTDI_{vol}$)

CT Scanner	Patient Age (y)			Patient Effective Diameter (cm)			Noise Value (HU)			$CTDI_{vol}$ (mGy)		
	Range	Mean	Median	Range	Mean	Median	Range	Mean	Median	Range	Mean	Median
Abdominopelvic CT protocol with contrast administration												
A	22.0–91.0	61.5	62.3	20.3–44.6	31.5	31.6	8.6–27.1	14.6	14.4	4.2–43.7	13.5	11.7
B	18.0–98.0	57.2	59.0	22.2–46.8	32.6	32.3	10.6–28.1	15.7	15.6	3.7–42.2	10.6	9.0
Chest CT protocol without contrast administration												
A	18.0–97.0	65.5	67.6	23.0–42.5	33.3	33.4	8.9–27.5	12.7	12.1	2.2–36.7	9.9	9.9
B	18.0–94.0	61.4	64.9	18.4–41.5	30.4	30.6	10.2–31.1	14.8	14.3	3.2–27.2	7.2	7.1

Note—Scanner A was a Discovery CT750HD (GE Healthcare), and scanner B was a Somatom Definition Flash (Siemens Healthineers).

concept, image quality should likewise be measured per procedure. Prior studies [6–8] have shown that it is possible to automatically measure image quality features, namely contrast, noise, and spatial resolution, on patient images. Since 2015, our institution has implemented a performance monitoring system incorporating automated techniques to measure the image quality attributes of CT examinations alongside dose metrics of the procedures [7, 9, 10].

As a first step toward extending the concept of DRL to include image quality, the purpose of this study was to develop a method to define new radiologic reference levels that simultaneously include image noise and dose metrics from clinical patient populations. The objective was to use the DRL framework in targeted reference values as a means to improve consistency of clinical performance. The method included medians and ranges associated with dose metrics and noise across a large cohort of clinical examinations. Because the data were intrinsically size dependent, the strategy included categorizing the examinations into different patient size ranges. For a given size range and clinical protocol, median values and interquartile intervals were used to define dose and noise reference levels and reference ranges to serve as quantitative surrogates of safety and quality in CT examinations.

Materials and Methods

This study was performed in compliance with HIPAA and was determined to be exempt from institutional review board requirements. The data were supplied from our institutional performance monitoring system (METIS, Duke University), which provides a database of scanner specifics, acquisition parameters, $CTDI_{vol}$, and patient size calculated as the patient effective diameter according to American Association of Physicists in Medicine report 204 [9, 11]. The system also offers measurements of image noise values according to a method the details and validation of which were described in an earlier study [7].

Our study included 2851 examinations (September 2016–February 2018) performed on adult patients (> 18 years old) with two scanner models (scanner A, Discovery CT750HD, GE Healthcare; scanner B, Somatom Definition Flash, Siemens Healthineers) and two clinical protocols: abdominopelvic CT with contrast administration and chest CT without contrast administration. Only diagnostic series were considered. Localizer, contrast-enhanced monitoring, contrast-enhanced premonitoring, and reformatted series were excluded by filtering out data with series descriptions corresponding to these types of scans. Between manufacturers, images had different slice thicknesses,

TABLE 3: Noise Reference Level, Noise Reference Range, Dose Reference Level, and Dose Reference Range for Abdominopelvic CT Protocol With Contrast Administration

Reference Size Range (cm)	No. of Examinations	Noise Reference Level (HU)	Noise Reference Range (HU)	Dose Reference Level (mGy)	Dose Reference Range (mGy)
21.0–24.9	56	10.1	9.4–11.8	5.0	4.4–5.6
25.0–28.9	238	11.6	10.5–12.6	6.5	5.7–7.8
29.0–32.9	322	11.6	10.3–12.8	9.2	7.9–11.1
33.0–36.9	266	11.3	9.6–12.9	12.1	9.6–17.3
37.0–40.9	134	12.1	10.7–13.7	16.7	12.6–20.5

so for consistency, all noise values were adjusted to a reference 5-mm slice thickness according to the following equation [12]:

$$noise \propto \frac{1}{\sqrt{slice\ thickness}}.$$

Scanning parameters, protocol names, patient ages, patient effective diameters, noise, and dose data are summarized in Tables 1 and 2.

In accordance with the latest U.S. DRL survey [13], the examinations were categorized into five reference patient size ranges: 21.0–24.9 cm, 25.0–28.9 cm, 29.0–32.9 cm, 33.0–36.9 cm, and 37.0–40.9 cm. For a given protocol, median, 25th percentile (first quartile), and 75th percentile (third quartile) noise and $CTDI_{vol}$ values were calculated for each reference size range. We used $CTDI_{vol}$ as a dose index because it is largely scanner independent. The following reference levels and reference ranges were defined for dose and noise in each size range and for each clinical protocol: noise reference level—median noise value across examinations; noise reference range—noise interquartile interval across examinations (difference between first and third quartiles); dose reference level—median $CTDI_{vol}$ value across examinations; dose reference range—$CTDI_{vol}$ interquartile interval across examinations.

TABLE 4: Noise Reference Level, Noise Reference Range, Dose Reference Level, and Dose Reference Range for Chest CT Protocol Without Contrast Administration

Reference Size Range (cm)	No. of Examinations	Noise Reference Level (HU)	Noise Reference Range (HU)	Dose Reference Level (mGy)	Dose Reference Range (mGy)
21.0–24.9	63	11.5	11.0–11.9	4.7	4.2–5.1
25.0–28.9	270	12.8	12.1–13.5	5.1	4.0–6.0
29.0–32.9	621	12.9	12.0–13.9	7.1	6.0–8.2
33.0–36.9	631	12.1	11.3–13.6	11.0	9.1–12.9
37.0–40.9	192	12.3	11.5–14.0	14.6	12.5–15.5

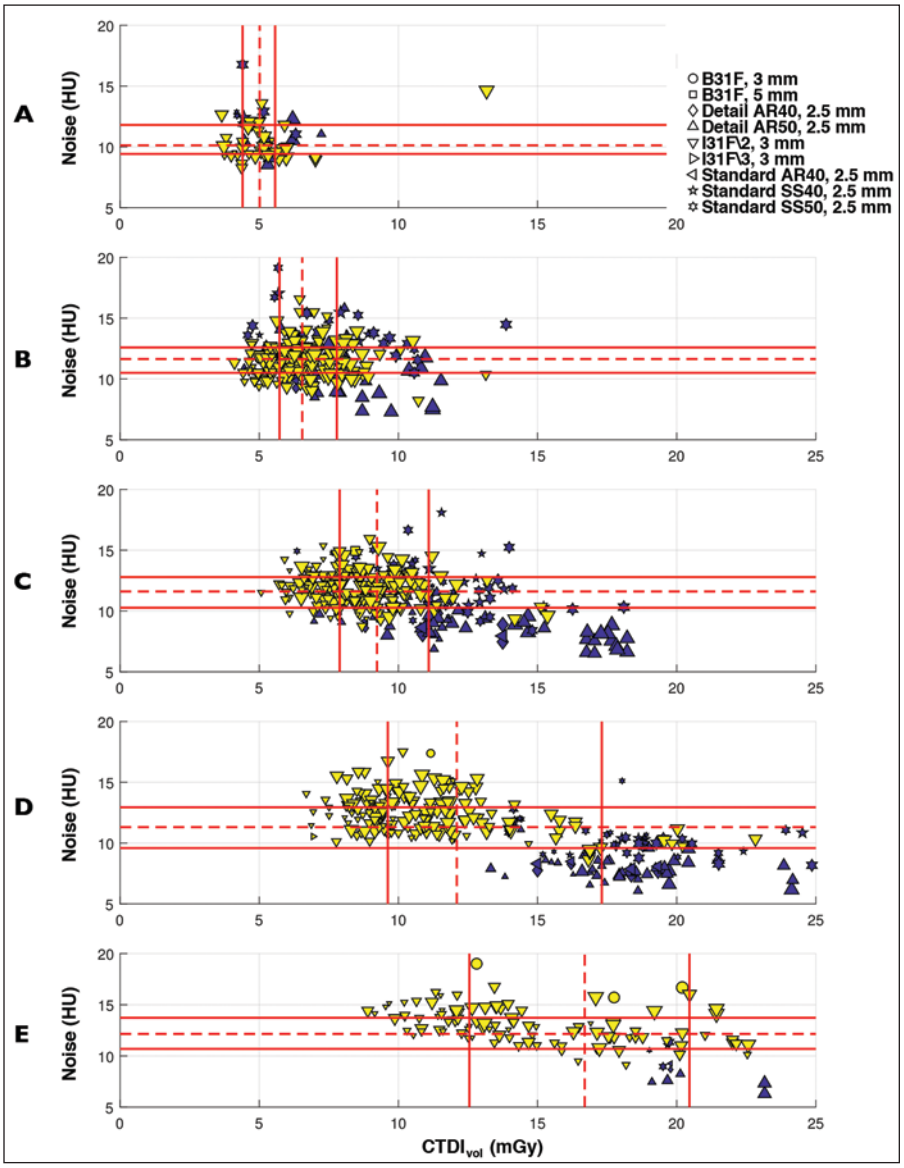

Fig. 1—Scatterplots show noise and dose reference levels and ranges for abdominopelvic CT protocol with contrast administration (1016 examinations). Solid lines indicate 25th and 75th percentiles; dashed lines, median values. Blue indicates scanner A (Discovery CT750HD, GE Healthcare); yellow, scanner B (Somatom Definition Flash, Siemens Healthineers). Shapes indicate reconstruction algorithms. Marker size correlates with patient diameter within range (larger markers indicate larger patients). Noise values are adjusted to reference 5-mm slice thickness. $CTDI_{vol}$ = volume CT dose index.
A, Reference patient size, 21.0–24.9 cm (n = 56).
B, Reference patient size, 25.0–28.9 cm (n = 238).
C, Reference patient size, 29.0–32.9 cm (n = 322).
D, Reference patient size, 33.0–36.9 cm (n = 266).
E, Reference patient size, 37.0–40.9 cm (n = 134).

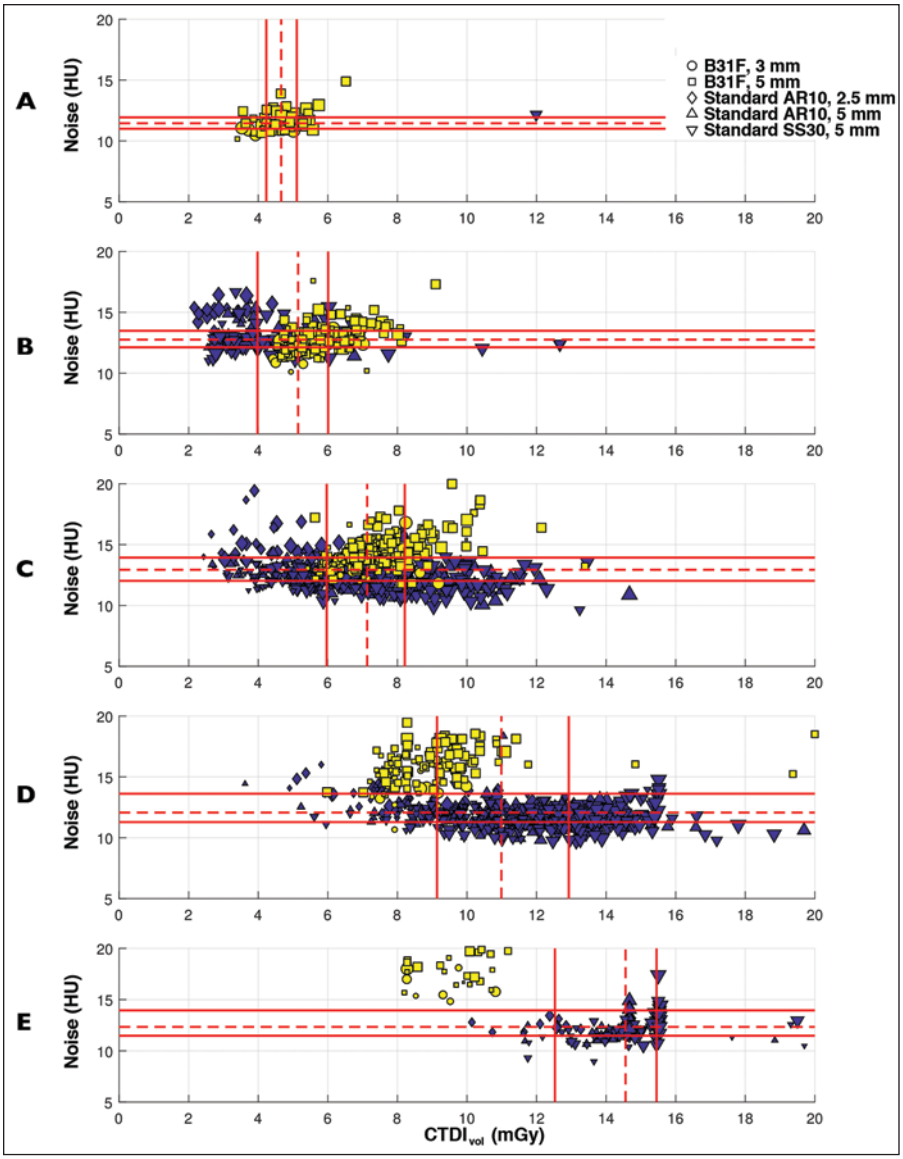

Fig. 2—Scatterplots show noise and dose reference levels and ranges for abdominopelvic CT protocol with contrast administration (1777 examinations). Solid lines indicate 25th and 75th percentiles; dashed lines, median values. Blue indicates scanner A (Discovery CT750HD, GE Healthcare); yellow, scanner B (Somatom Definition Flash, Siemens Healthineers). Shapes indicate reconstruction algorithms. Marker size correlates with patient diameter within range (larger markers indicate larger patients). Noise values are adjusted to reference 5-mm slice thickness. $CTDI_{vol}$ = volume CT dose index.
A, Reference patient size, 21.0–24.9 cm (n = 63).
B, Reference patient size, 25.0–28.9 cm (n = 270).
C, Reference patient size, 29.0–32.9 cm (n = 621).
D, Reference patient size, 33.0–36.9 cm (n = 631).
E, Reference patient size, 37.0–40.9 cm (n = 192).

quartile interval across examinations (difference between first and third quartiles). Median (as opposed to mean) values were used for consistency with 2017 ICRP recommendations [3].

Results

A total of 2793 examinations (98%) were within the five patient size reference ranges. The noise reference level, noise reference range, dose reference level, and dose reference range results are summarized in Tables 3 and 4 and plotted in Figures 1 and 2. Minimums of 56 and 63 and maximums of 322 and 631 examinations were included in each patient size range for abdominopelvic CT with contrast administration and chest CT without contrast administration, respectively. The reported data show how dose increased with patient size while noise reference levels remained fairly constant as a function of size. Furthermore, scanners from different vendors exhibited different trends in terms of dose and noise across patient size as a consequence of different strategies for automated tube current modulation balance between image quality and radiation dose. Differences in noise and $CTDI_{vol}$ values between vendors increased with patient effective diameter. In particular, scanner A data showed dose increasing with patient size while noise decreased. Scanner B data, however, showed both dose and noise increasing with patient size.

Discussion

We propose and calculate new reference levels and ranges that simultaneously consider image noise and radiation dose information across a clinical patient population (i.e., noise reference levels, noise reference ranges, dose reference levels, and dose reference ranges) for two clinical protocols: abdominopelvic CT with contrast administration and chest CT without contrast administration. The defined levels and ranges represent a first approach to more comprehensive performance reference level definitions in CT. Such a comparison is best made by use of an informatics system that can efficiently and in an automated manner record image quality, dose, and patient size information.

For a given protocol and patient reference size range, noise reference range provides a scanner-independent noise reference interval, and noise reference level provides the lev-

el that should ideally be targeted. Likewise, dose reference range represents a scanner-independent dose reference interval, and dose reference level represents the reference value that should ideally be targeted. These newly defined metrics can be used for multiple purposes. First, they can help identify series with poorer image quality than others. Second, they can help identify high-dose examinations: noise values below noise reference range could be flagged for further investigation to determine whether the radiation dose was unnecessarily high. Furthermore, noise and dose values above or below the reference ranges can be investigated with regard to the possible causes of outliers (e.g., patient malpositioning, artifacts, scan FOV). Third, simultaneous assessment of size-based image quality and radiation dose provides unique insights into the ways in which different vendors pursue different automated tube current modulation strategies [14–16]. Finally, comparison of patient population data by use of reference levels and ranges provides quantitative information for optimizing protocols and improving overall CT performance.

Regarding the potential for a new optimization paradigm, Figures 1 and 2 show different trends for different vendors, as expected, in terms of noise and dose distributions across patient sizes. Dose increased with patient size [9, 10], but noise decreased in scanner A and increased in scanner B. This information can be used for optimization as shown in Figure 2 and noise reference ranges for a chest CT protocol without contrast administration. To achieve consistent image quality, scanner A procedures could be redesigned by increasing the dose for smaller patients and decreasing the dose for larger patients, and the opposite for scanner B. Patient-specific consistency can be achieved by making the patient the focus of the procedure, necessitating scanner-independent metrics. Therefore, it was essential to calculate reference levels and ranges simultaneously, including examinations performed with all scanners. It was also essential to calculate protocol-specific reference levels and ranges because differences in anatomy and diagnostic task can affect the relation between image quality and radiation dose.

The approach we describe represents a first attempt to address what the ICRP states in publication 135: "The Commission emphasizes the importance of the link between the amount of radiation applied to the patient and image quality. Application of DRL values is not sufficient for optimization of protection. Image quality must be evaluated as well" [3]. Despite claiming the importance of image quality in radiology optimization, the ICRP and other international committees and associations have not made a clear distinction between qualitative image quality evaluations and quantitative alternatives to enable precise optimization of imaging examinations, except in a 2018 recommendation from the International Atomic Energy Agency [17].

In recent years, different approaches to radiation dose and image quality optimization in CT have been divided into three categories. One approach considers only radiation dose reduction [18]. A second approach is embodied in studies based on phantom radiation dose and quantitative image quality analysis [19]. A third approach considers a cohort of patients in which image quality is qualitatively and quantitatively evaluated by trained observers [20, 21]. These models, although innovative and informative, do not consider image quality at all, provide information only concerning highly constrained and simplistic setups (phantom studies), or introduce a subjective source of uncertainty (not automated measurements) through resource-heavy and subjective observer studies. We propose an advancement in the hybridization of automated quality and dose metrics into a paradigm of performance as an optimization tool informed by data from clinically performed CT examinations. This approach is consistent with the DRL surveys that establish national and international DRLs [13] and can be further implemented in the same manner.

This study had a few limitations. Diagnostic image quality was evaluated only for two adult clinical protocols in terms of noise magnitude. In future studies it will be important to define reference levels for other image quality descriptors, such as spatial resolution, noise spectra, and contrast. However, the approach described in the study can be readily extended to other image quality indexes [6, 8] and to other adult and pediatric clinical protocols. Furthermore, the results can be correlated with image quality observer estimations. Concerning dose metrics, $CTDI_{vol}$ was chosen as a scanner-independent metric and because it is strictly related to scanner output. However, future work can consider other dose metrics, including dose-length product, size-specific dose estimates [22], organ dose [23–25], and effective dose. Finally, the method used in this study did not prospectively target dose or image quality based on strict diagnostic performance, such as detectability index [26, 27], but based it on examination statistics. Future work will ideally consider that possibility.

Conclusion

Extensions to DRLs are proposed and established for clinical CT populations. The new performance reference levels and ranges (noise reference level, noise reference range, dose reference level, dose reference range) ensure that radiation risk and clinical benefit are quantitatively considered in the CT optimization process. These analyses are enabled by a performance monitoring system that captures radiation dose and image quality as metrics that can simultaneously describe the actual imaging systems output.

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