Review paper

Radiation dose monitoring in computed tomography: Status, options and limitations

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ABSTRACT

In the last few years there has been an increasing interest on radiation dose to patients undergoing various diagnostic or therapeutic procedures with the use of ionizing radiation. Especially for CT examinations and interventional procedures, where it is known that patient doses are much higher than conventional radiography, new norms have been published that require to have appropriate radiation dose indices registered in the patient medical record. Because of these demands, dose monitoring has been recommended and adopted into many clinical practices as a routine procedure for every patient and every examination. Dedicated dose monitoring systems (DMS) that facilitate data collection and processing, statistical comparisons, reporting and management of radiation dose related information have been devised and are being used worldwide.

In this review paper, a brief flashback to the reasons that necessitated dose monitoring in radiology will be first presented. Furthermore, since the focus of this manuscript is on CT, the CT dosimetry principles and metrics will be summarized. The limitations of these metrics will be also discussed, so that DMS users are aware of the semantics of the parameters shown in the DMS reports. The operation of DMS systems will be outlined to make users aware of functions, limitations, and available options of DMS systems. Furthermore, the usefulness of DMS systems as an optimization tool will be presented and discussed. Finally, information about the DMS solutions available in the market and relevant links will be presented.

1. Introduction

The discovery of X-rays by Wilhelm Conrad Röntgen on 8th November of 1895, earned him the first Nobel Prize in Physics in 1901, but undoubtedly it was a milestone for medicine also. Immediately after his discovery, X-rays were used for imaging and therapy, and very soon it was understood that X-rays apart from beneficial could also be harmful. The first skin burn was reported in 1896 from the use of X-rays for radiation therapy. The 1897 publications reported more cases of skin damage as well as radiation-induced cataract. In 1902 there was the first report of X-ray induced cancer, while in 1911 the occurrence of cancer in 94 individuals in Germany, 50 of them being radiologists, was reported.

The experiments of the Hermann Joseph Muller on *Drosophila* fruit flies documented the induction of mutation by X-rays and earned him the Nobel Prize in Physiology or Medicine in 1946. His work led to the Linear No Threshold hypothesis of radiation damage (LNT), according to which, lifespan decrease and cancer/mutation risk remains linear as the radiation dose goes down to zero. LNT model was adopted by the

nuclear industry for safety purposes, in order to ensure employers take precautionary steps to protect employees. Though other models have been proposed, which suggest that the risk decreases at low doses more than the LNT model predicts and may be zero below a threshold, or that low radiation doses may be even beneficial (because of hormesis), the LNT model is currently the prevailing model for estimating the risk from exposure to low levels of ionizing radiation, like those currently used in medicine for diagnostic imaging purposes [1]. This means that all radiation doses, however small, built up and increase risk and therefore should be taken into account.

While the risks from the use of ionizing radiation for diagnostic purposes were well known among the professionals in the field of radiology and nuclear medicine [2–4], the controversial article of Brenner et al. [5] increased awareness and concerns of these risks among medical professionals and the public. That article reported that radiation from two or three CT scans, results in a detectable increase in the risk of cancer, especially in children. Given the fact that CT is currently the major contributor of radiation dose to patients undergoing diagnostic X-ray examinations, the alarming results of this article were

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extensively debated not only by the scientific community but also by the press. However, what undoubtedly sparked a big change and set new standards for the dosimetry software of CT scanners [6], was the occurrence of skin injuries in brain perfusion CT procedures in USA, which were covered by the press [7–9]. In these cases, the risks were no longer postulated; the adverse effects of X-ray overdose were visible and indisputable. Despite concerns over radiation dose, it is a fact that when CT examinations are justified and performed appropriately, provide invaluable information that help in diagnosis, staging and treatment of several clinical maladies. Thus, justification of CT should be established in order to ensure a favorable clinical benefit versus potential radiation-induced harm equation.

Following the NEMA XR 25-2010 standard [6], CT manufacturers added to the existing dosimetric software which was calculating the volume computed tomography dose index ($CTDI_{vol}$) and dose length product (DLP) from each individual scan series and the total DLP for the whole examination, a new feature named Computed Tomography Dose Check (CT Dose Check). This feature produces dose-related notification and alert messages to inform operators prior to scanning if the estimated dose would exceed the preset levels of $CTDI_{vol}$ and/or DLP which can be specified by the user for specific CT examination protocols [10]. Notification values apply to individual scan series, while alert values apply to an entire exam. However, what was really new in this feature is that for the first time skin dose was also considered. CT dose check also produces an alert pop-up window, when the $CTDI_{vol}$ to any specific position of the scanned anatomic position reaches a predefined value. The preset is 1000 mGy (according to USA Food and Drug Administration recommendations), which is half the threshold dose associated with the onset of skin injury [11]. When an alert is produced, the user has to log on and confirm that the warning has been taken into account in order to proceed with the scan.

According to the latest European Directive 2013/59/Euratom on radiation protection [12] and the International Basic Safety Standards (BSS) [13], which provided new safety requirements for medical exposures and a basis for national regulations. The directive requires recording of information related to radiation dose especially for CT and interventional radiology procedures, and for radiological equipment installed after 6 February of 2018. For these, the patient dose related parameters should be transferred to the examination record [12]. In an ideal circumstance, following the IAEA Smart Card/SmartRadTrack project and the Joint position statement rationale [14,15], all diagnostic examinations involving radiation should be recorded, including fluoroscopic, radiographic, mammographic and nuclear medicine examinations, to allow monitoring of the exposure history of each patient. While such universal application is challenging, to meet this requirement for CT examinations on a local or regional level, a system with central database is needed to collect the dosimetric information for each CT examination regardless of the scanner location, so that all information for each specific patient is stored in his/her dosimetric record.

In response to this need, commercial software packages were developed that connect (directly or via PACS) with CT scanners and other diagnostic units, to collect all available data into a database, where authorized personnel can access and analyze data for each examination. Data collection and communication between systems is performed using Digital Imaging and Communications in Medicine (DICOM) and Health Level Seven (HL7) standards, integrating the Healthcare Enterprise (IHE) Radiation Exposure Monitoring (REM) profiles [16,17]. In the following, the capabilities of these systems in terms of patient dose data management, their contribution to optimization of examination protocols and their limitations will be presented and discussed in detail.

2. Basic principles, metrics and limitations of CT dosimetry

CT dosimetry is based on a quantity named $CTDI_{100}$ which is

defined by the following equation [18]:

$$CTDI_{100} = \frac{1}{NT} \int_{-50mm}^{+50mm} D(z) dz \quad (1)$$

where N is the number of axial slices of thickness T acquired during a single axial rotation, $D(z)$ is the dose profile along the axis (z) which is perpendicular to the scanning plane and 100 mm (from –50 mm to +50 mm) is the integration range with respect to the X-ray beam central axis. In this way the dose profile, that has a Gaussian like shape, is converted to a step like dose profile, confined within the geometrical limits of the X-ray beam of width NT. $CTDI$ is given in units of absorbed dose, usually in mGy ($1 \text{ mGy} = 10^{-3} \text{ Gy} = 10^{-3} \text{ J/kg}$). $CTDI$ is a widely accepted and used quantity in CT scanner displays. It must be clarified that the actual quantity measured is air-kerma and not dose, and therefore the $CTDI$ is essentially the CT air-kerma index [19,20]. While we use the word ‘dose’ to be in line with the original terminology, the correct physical quantity is air-kerma.

For dose measurements, a pencil type ionization chamber 100 mm long and two 15 cm long cylindrical PMMA phantoms of diameter 16 cm (to represent a human head) and 32 cm (to represent a human body) are used [20,21]. These phantoms have holes to fit the ionization chamber at their center and their periphery (set at 3, 6, 9 and 12 o'clock positions, 1 cm below the phantom surface). For each phantom dose measurements are acquired at the center and the four peripheral positions using axial scanning and the weighted $CTDI$ ($CTDI_w$) is derived using the following equation:

$$CTDI_w = \frac{1}{3}CTDI_c + \frac{2}{3}CTDI_p \quad (2)$$

where $CTDI_c$ and $CTDI_p$ are the $CTDI_{100}$ values measured at the center and the average of the four peripheral positions, respectively. In the way that $CTDI_w$ is defined, it represents the average absorbed dose across the scanned slice of the phantom.

Since currently most of the CT scans are acquired using helical rather than axial scanning the volume $CTDI$ ($CTDI_{vol}$) was introduced [20,21], described by the following equation:

$$CTDI_{vol} = \frac{CTDI_w}{pitch} \quad (3)$$

where pitch is the ratio of the CT table travel and the beam width (NT) per helical rotation.

Currently, CT scanners report the $CTDI_{vol}$ values and PMMA phantom size (16 or 32 cm), whether for axial or helical scans, which are specific for the phantom and the scan parameters used (collimation, pitch, focus size, bowtie filter, kVp, mAs). Keeping all the rest of the scan parameters constant, smaller pitch values result in an increased $CTDI_{vol}$.

Since using the same scan parameters to scan unequal scan lengths (L) will result to the same $CTDI_{vol}$ values, an additional metric had to be introduced to account for the increased risk that the irradiation of larger areas of the body entails. Thus, the dose length product (DLP), which currently is referred to as air kerma-length product [15,16], was defined as the product of $CTDI_{vol}$ and the scan length (L) [20,21]:

$$DLP = CTDI_{vol} \times L \quad (4)$$

It must be noted that L is the actual scan length and not the planned scan length, since helical scanning involves a whole or partial rotation before the start and after the end of the planned scan length, thus adding to it a length (referred to overscan or overranging) that while it is irradiated it is not included in the CT reconstructed images [22]. As aforementioned, DLP is shown along the $CTDI_{vol}$ when a scan series is programmed, to inform the user prior to actual scanning. After the end of each examination, a Dose Report is produced with the $CTDI_{vol}$ and DLP values for each individual scan series performed and the cumulative DLP value for the whole examination. It is important and necessary to verify the CT dose display by performing actual measurements on the

Fig. 1. Dose Report Images from a Toshiba Asteion 64 CT scanner. The first page (a) gives an overview of the whole exam, including the total DLP, mAs and scan time. The second (b) and third (c) pages display information about each scan series in terms of acquisition protocol name, CTDI_{vol}, DLP and total mAs (SD is the noise index value for the AEC protocol used).

CT scanners during acceptance testing and on a regular basis thereafter.

While the above equations remain the basis of CT dosimetry, the advent of CT multidetector scanners with actual beam widths up to 16 cm, necessitated revisiting and re-designing CT dosimetry. As aforementioned, CT dosimetry measurements are based on the use of a pencil type ionization chamber 10 cm long and a phantom 15 cm that obviously could not encompass the whole beam width of such CT scanners. These problems were addressed in the AAPM-TG111 report [23], where with the use of a small thimble ionization chamber, long PMMA phantoms and helical scanning, the increase of the mid-slice dose with larger beam widths, larger phantom and scan lengths was studied. This report introduced a new rationale in the field CT dosimetry, that was completed with the recent AAPM TG200 publication [24], which follows up the initial report and consolidates old and new measurement practices, retaining however the basic dose metrics intact. More details about CT dosimetry for wide cone beam scanners can be found elsewhere [25].

It is well known that to quantify the radiation-induced cancer risk from different modalities and partial body irradiations the quantity of choice [26] is the effective dose (E). E is the sum of the equivalent doses (equivalent dose is given in Sv and for X-rays and electrons it is numerically equal to the absorbed dose) of all irradiated radiosensitive organs multiplied by a weighting factor specific to each organ and tissue, as described in the ICRP 60 [27] and ICRP 103 [28] publications. In the era when CT scans were performed using a constant mAs value, an estimate of E and organ doses could be obtained using free or other commercial software packages and data from Monte Carlo simulations [29,30]. An easy method used for calculating E was the multiplication of DLP by a conversion factor k , specific to the exam type and the patient age, for typical sized adult and pediatric patients [21]. The introduction of tube current modulation techniques introduced further difficulties in E estimation, and new methods for estimating E and organ doses were developed [31,32], though k -factors are still routinely used.

However, apart from the inaccuracies of these methods and the inherent inaccuracies of k conversion factors, the major problem with

patient dose estimation in CT lies within the CTDI_{vol} values. While getting into details about the limitations of CTDI_{vol} is beyond the scope of this article, it can be briefly noted that the PMMA phantoms used are not representative of all, if any, patient sizes and shapes, not to mention the actual morphology and composition; therefore CTDI_{vol} and patient dose are fundamentally different [33]. Since the actual dose absorbed is strongly influenced by the patient size, the CTDI_{vol} does not accurately describe the average dose across a patient CT slice. Furthermore, CTDI_{vol} measures air kerma and not dose to tissue or water. To account for these, the concepts of size specific dose estimates (SSDE) and water equivalent diameter were introduced [34,35]. According to the respective methodology proposed, SSDE is calculated by multiplying the CTDI_{vol} value by a coefficient selected according to the patient size. Though SSDE values are doses to water/tissues and correct the CTDI_{vol} for the effect of patient size, their use for estimation of E and organ doses is not appropriate for the reasons explained elsewhere [34].

$$SSDE = CTDI_{vol} \times \text{patient body size - based coefficient} \quad (5)$$

Thus, users must remember that CTDI_{vol} and DLP represent CT output dose rather than actual patient doses. Despite their limitations, they play an important role in comparison and optimization of different CT protocols as well as in dose monitoring. Presently, neither SSDE nor E are displayed on the scanner user interface before or at the time of scanning.

2.1. Dose monitoring: A glance at the past

In the past, the CTDI_{vol} and DLP values were displayed on the CT control console monitor only while the examination was performed and they were lost after the examination was completed. Therefore, in order to perform a patient dose survey, the radiation technologist had to manually record these values along with the type of examination in a log book. Then these values had to be manually entered in a worksheet to allow statistical analysis. It is easily understandable, that in this way, a patient dose survey was a rather long and tedious procedure, which

Fig. 2. Dose Report Images from: a) GE Brightspeed 16; it provides the numerical scan range for each helical acquisition but does not include dose values for the scout (SPR), and b) Siemens Somatom Definition; it provides additional information on exposure time and the detector width that corresponds to the collimation configuration used. The first series is acquired with automatic exposure control (mAs/ref imply average used mAs/quality reference mAs for dose modulation). The other series were acquired with fixed 190 mAs.

could be performed only periodically and not in a routine basis.

The advent of Dose Report images allowed all dose related values to be captured and stored automatically as a pseudo-DICOM image, along with the other CT images of the examination. This dispensed with the need for manual recording of these values, but their manual entry in a spreadsheet was still required. Optical character recognition (OCR) based software was developed to eliminate this need also, facilitating and speeding up the data entry procedure. The amount of information reported in the Dose Report image varies depending on the CT manufacturer, but at minimum the scan protocol name, the CTDI_{vol} and DLP values are reported (along with patient demographics), while in some CT scanners the scan range, scan time, kV, and mAs values are also reported (examples are shown in Figs. 1 and 2).

For the analysis of dose data per scan series, to categorize each scan series in a specific examination or anatomic region, one had to use the examination protocol for identification. However, in many facilities it is not uncommon to use the same protocol for many examination types, e.g. an abdomen protocol could be used for an abdomen-pelvis or even a chest-abdomen-pelvis examination. When the scan length was included in the data of each scan series, it could be helpful to indicate cases where there is obviously inappropriate categorization (e.g. abdomen CT with a scan length of 70 cm). In general however, the only safe way to assign each scan series in the correct anatomic category was to review the image series or the lines on the respective scanned projection radiograph (SPR) image (referred to as scanogram, scout or topogram by various CT manufacturers) indicating the scan series start and end points.

2.2. Dose monitoring systems: Operation principles

Dose monitoring systems (DMS) offer solutions to many problems inherent to the manual and semi-manual procedures described above. Most DMS function from a server (physical, virtual or cloud-based) which is used for data capture, analyses, display of results, and distribution to other interfaced systems. With DMS, the data collection procedure is fully automated and it can be done in many ways using: OCR of the Dose Report images, analysis of the DICOM headers (both are useful mostly for older systems), DICOM-modality performed procedure step and analysis of the Radiation Dose Structured Report (RDSR) generated in all modern CT scanners [36,37]. Support for these RDSR objects appears in the DICOM Conformance Statement document of each CT scanner and other imaging modalities, which can be found on vendor websites [38].

DMS can be connected directly to the acquisition workstation of CT scanners, but the most common connection architecture used is for the DMS to be connected to the PACS system. This is very convenient when many imaging modalities which are already connected to the PACS are

going to be served by the same DMS. Since different modalities from different vendors will to be served by the same DMS, the DMS has to be vendor-independent. The DMS systems have access to all CT images acquired during the examination, to their DICOM headers but also to the RDSR, where all data for each irradiation event are recorded in detail. This means that patient demographic data, examination protocol and scan series acquisition protocol details, exposure factors, CTDI_{vol} and DLP values, scan ranges, etc. are all automatically recorded. DMS can be also connected to the Radiology Information System (RIS) and the Hospital Information System (HIS), e.g. if it is desired to have the dosimetric data recorded on the patient examination report along with the diagnosis. A schematic diagram of the connections used is given in Fig. 3.

Though some differences may exist between DMS systems from different manufacturers, the basic operations of DMS are described in the following, for DMS connected to PACS. The scanners are required to display CTDI_{vol} and DLP after SPR is acquired and scan acquisitions are planned. This “real-time” and prospective dose display, enable the users to modify scan parameters to reduce radiation dose if necessary. Since most DMS acquire data from PACS, they are not real-time monitoring solutions unlike the dose display on the scanner interface before or at the time of data acquisition. In a recent article published by Heilmair et al. [39], though the term “real-time monitoring” was used, it is acknowledged that the data were retrieved from PACS after the completion of the examination. However, it is possible to have DMS monitor screen display institutional and protocol-wise dose levels from other patients or the same patient, at the time of scanning. This can enable the users to compare and modify radiation dose if necessary should the CT displayed doses differ substantially from the DMS displayed levels. Some institutions (such as Massachusetts General Hospital - MGH) post their “reference dose values” from prior dose data recorded in the DMS for typical protocols as a guide to their CT technologists. However, even with such an arrangement, DMS are not “real-time”, since the data shown are historical and not specific to the data shown in the CT control console monitor for the examination performed at that time.

2.2.1. Data collection and processing

The first task of DMS is to record all demographic, examination type and dose related data, for each examination performed. In the usual connection architecture (DMS connected to PACS) once an examination has been completed and sent to PACS then a new dosimetric record, for the specific patient and examination, is generated in the DMS (if the patient has already dose records from other previous examinations all those records can be viewed under his name or his unique identification number). For DMS operating at a regional or national level, the unique identification number of a patient must remain constant (e.g. social security number or personal identification number).

Fig. 3. Graphic workflow chart displays a typical network architecture among the hospital systems, acquiring and managing patient data and images, from various diagnostic modalities. PACS is considered part of the RIS system, performing additional functionalities, including receiving data from the HIS (e.g. patient demographics and scheduled appointments) forwarded to the modalities (DICOM worklist) and vice versa (e.g. Diagnosis reports). The dashed line between DMS and Modalities represents an additional, yet sometimes necessary association, to the DMS-PACS connection which is primarily implemented.

While a single-series CT exam has one or more sets of $CTDI_{vol}$ and DLP (one for planning radiograph and other for the helical dataset), multiple sets of $CTDI_{vol}$ and DLP are generated for multiphase exams which are common with CT abdomen-pelvis and CT angiography. For example, let's assume that a patient has undergone a multiphase abdomen CT exam. To perform this exam, the CT scanner operator will select the respective examination protocol, which is comprised by one or two SPRs (anteroposterior and lateral) and different helical acquisitions or series (such as non-contrast, separate post-contrast phases that include, and are not limited to, arterial, portal venous, and delayed phases). After the SPRs are performed, the CT scanner operator prescribes the start and end location for each scan phase. Frequently, for arterial phase CT, sequential or axial scan series are generated with use of contrast bolus tracking or test bolus. Certain scanners such as dual-source CT generate two separate sets of $CTDI_{vol}$ and DLP for each phase acquired with dual-energy CT acquisition. Other vendors do not split the dual-energy CT acquisition doses despite tube potential switching between high and low kV. For multiphase CT, in addition to the series level $CTDI_{vol}$ and DLP, the scanner also generates a total DLP for the entire exam (sum of all series DLP). Since, the total DLP depends not only on the number of series acquired but also the scan parameters applied for acquisition of each phase, by itself the total DLP may not provide the complete information. After the SPRs are performed, the CT scanner operator prescribes the start and end location for each scan phase. The moment that the CT operator completes the examination, the dose report images and RDSR are created. These reports along with all images (primary and secondary CT axial slices and MPR images) are all sent to PACS.

Subsequently, PACS transmits to the DMS all those data (RDSR and/or DICOM data of CT images, and/or the Dose Report image), which the DMS requires to fill the new dosimetric record. Of course, the most essential parameters are the total DLP for the whole exam and the $CTDI_{vol}$ and DLP values for each individual acquisition. So, under the main exam there will be in total five (or six) rows: one (or two) for SPR (s) and four for the helical scans described above. Not all scanners generate dose indices for SPRs. The additional series (secondary or derived reconstructions or reformats) of axial or MPR images have no dosimetric significance and are ignored. An example of a dosimetric record for an examination with one SPR and three helical acquisitions is given in Fig. 4.

What other information is made available to DMS? Some DMS use CT images from the PACS to assign or confirm the body regions of scan

acquisition in addition to the automatic estimation of effective diameter (for SSDE) and water equivalent diameter (WED). The SPR images are routinely used, from which important information can be derived. The SPRs are used by the CT scanner to determine the attenuation properties of the patient and determine the tube current modulation that is needed to obtain a certain image quality, as required by the acquisition protocol [40,41]. The same images are used by the DMS to estimate the patient size [42,43] which is required for SSDE calculations, though some systems may also utilize the axial CT images [34,35]. If part of patient's periphery is missing e.g. because of patient anatomy being beyond the scan field of view (SPR - in large patient body habitus) or large off-center positioning and the patient size cannot be determined, a warning is posted that SSDE cannot be calculated. Regarding off-center positioning, a few DMS utilize CT images (SPRs or CT axial images), to calculate deviations from the ideal positioning [39]. Correct patient positioning (i.e. isocentric) is of great importance and can be considered as a supplementary examination quality index, since tube current modulation and image quality may be adversely affected by incorrect patient positioning [44–47].

For the DMS to be able to proceed to comparisons with reference values of dose metrics, it is required to identify the examination type and the anatomic region scanned in each individual acquisition. The latter is needed also for calculations of E , since the k-factors (used to convert DLP to E) depend on the anatomic area examined. The identification of examination type and individual acquisitions can be a big problem, for two reasons: first because a standard nomenclature concerning the naming of CT protocols is not universally applied and second, because examinations protocols may not be used consistently to denote a specific exam and scan series acquisitions. In cases of diagnostic facilities where more than one CT scanner exists, it is not uncommon to have in different CT scanners different protocol names for the same exam type. However, this is not a problem for DMS, where "master protocols" are used to merge all the different protocol names denoting the same examination (e.g. CT chest and CT thorax), so that they are recognized by the DMS as being the same exam type and are categorized in the same group. Therefore, in a properly configured DMS system, if operators are consistently using the proper examination protocol for each acquisition, it can be expected that each examination and scan series will be correctly categorized.

Assigning exams and acquisition protocols to respective master protocols that exist in DMS, is part of the DMS configuration and should be done by authorized users only (typically, a CT operator who is most

Studies' History: - CT Abdomen and pelvis with contrast - CT -

Study Information | Quality | SSDE and Positioning

Patient Information

ID: [REDACTED]
 Name: [REDACTED]
 DoB: [REDACTED]
 Age: 64
 Sex: F
 Pregnancy: [REDACTED]
 Height: [REDACTED] (cm)
 Weight: [REDACTED] (Kg)
 BMI: [REDACTED]
 Save | More Info...

Study Information

Study UID: [REDACTED]
 Study ID: CABPEC
 Acc. Number: [REDACTED]
 Admission ID: [REDACTED]
 Modality: CT
 Study Description: CT Abdomen and pelvis with contrast
 Study Date: [REDACTED]
 Procedure: CT Abdomen and pel... Analyze Reassign
 Source Capture: SR Save File
 0 document(s)

Protocol: 02ABDOMENROUTINEPLAIN_CONTRAST... Analyze
 Institution: [REDACTED]
 Station: [REDACTED]
 Manufacturer: SIEMENS
 Model: SOMATOM Definition Edge
 Operator: [REDACTED]
 Perf. Physician: [REDACTED]
 Req. Physician: UNKNOWN^UNKNOWN
 Ignore in stats: ☐
 Image Quality: Image Quality is not defined

Dose Information

Anat. Region: Abdomen Pelvis Organ Dose CT
 Alert Message: [REDACTED]
 Comments: [REDACTED]
 Tags: [REDACTED]
 Save

Total Eff. Dose: 56.35 mSv
 Total DLP: 3296.14 mGy.cm
 Total DLP 32: 3296.14 mGy.cm
 IR Events: 3
 DLP w/acq: 1098.36 mGy.cm
 CTDIvol w/acq: 21.63 mGy

Contrast Product Information

APPLIED

Ingredient: [REDACTED] Route: [REDACTED]
 Total Dose: 0.00 ml Start/End Time: 12:38:46 AM - 12:38:46 AM
 Concentration: 0.00 mg/ml Volume: 0.00 ml
 Flow Rate: 0 ml/s Flow Duration: 0 s

Acquisitions

Acq. Number	Type	Acq. Protocol	Description	Anatomy	Scanning Length (mm)	CTDIvol (mGy) Level 1: 17 Level 2: 34	SSDE (mGy)
1	LOCALIZER	TopoAbdomen		Abdomen	384.00	0.02	
2	HELICAL	Abdomen Plain		Abdomen	535.00	22.13	27.66
3	HELICAL	Abdomen +C		Abdomen	538.00	21.40	26.75
4	HELICAL	Abdomen +C		Abdomen	538.00	21.37	26.71

Fig. 4. Graphics User Interface page (Medsquare RDM) depicts the dosimetric record of a patient that underwent a CT abdomen and pelvis with contrast with one planning radiograph (SPR) and three helical acquisitions. In the upper part of the page patient, institution and study related information is given. In the middle part, on the left side, the total values of E , DLP, DLP32 (DLP32 implies DLP calculated for 32 cm phantom, which is equal to DLP for body CT) and weighted DLP and CTDI_{vol} values (DLP w/acq and CTDI w/acq) are given. In the right side, under the Alert Message, all CTDI_{vol} and DLP values are orange because they have exceeded the reference values for Level 1 alert type for these acquisition protocols. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

well-verse with the protocols and patient scanning practices), since it affects many aspects of the DMS operation. In the configuration menu, the authorized user can also define for each master protocol group, reference values for CTDI_{vol} and DLP (for individual acquisitions), and for total DLP (for the whole exam). Usually there are two reference values for each dose metric, one low and one high, which if exceeded, produce respective alerts. More information about alerts and their management is given in the next subsection. An example of master protocols for abdomen region acquisitions is given in Fig. 5.

Concerning the E and organ dose calculations, depending on the DMS product and its optional characteristics, E may be simply calculated by multiplying DLP by k-factors for adults or children of certain age categories, depending on patient age and the anatomic region scanned. Therefore, each master protocol for individual acquisitions must be assigned with respective k-factors for adults and children and DMS usually have a preset list of such k-factors for specific exams. Some DMS offer more elaborate methods for calculations of E and organ dose estimates, for all organs modeled in the phantom(s) used. In some DMS a detailed calculation of organ doses and E is obtained, taking into account the tube current modulation (the CTDI_{vol} varies along the scanning direction) and using an anthropomorphic phantom, either stylized (geometrical) or a realistic one (produced using CT images of actual patients and organ segmentation). The basic stylized phantom is the MIRD [48], which represents a hermaphrodite patient of typical size, and which has been extensively used in Monte Carlo simulations to derive the k-conversion factors currently used. The Cristy/Eckerman

phantom family contains 20 stylized phantoms of various sizes and ages. Furthermore, pregnant phantoms of various sizes and gestation periods (I, II and III trimester) are also available and are used in some DMS. However, realistic phantoms better mimic actual patients (even pregnant ones), and in some DMS systems there is a large library of such realistic phantoms and the one that matches the specific patient in terms of his age, size and gender can be selected. The literature on anthropomorphic phantoms and their use for patient dose calculations is quite extensive and it is not limited to the referenced studies [48–60]. A detailed description of 50-years of evolution in the design of anthropomorphic phantoms can be found elsewhere [56].

In some DMS, the SPRs are used to match the patient to a phantom of similar size. Since the table positions of the SPR and each scan series are included to the data sent to DMS, the DMS software can determine what part of the SPR is scanned during each acquisition. After matching of the patient with a phantom of similar size, the DMS can determine not only of the geometrical but also of the anatomic start and end points of each the scan series. Therefore, the actual examination can be simulated in the phantom and calculate E , organ doses, and in some cases, even cancer risk estimates [57–66]. However, E values, organ doses and risk estimates reported within DMS should be used with caution, because apart from the inherent limitations of such calculations, in most cases they are not patient specific [36].

Regardless of the method used to calculate the E and organ doses, medical physicists should verify that dose data are correctly transferred from the CT scanner to DMS, and that SSDE, effective and organ dose

Fig. 5. Graphics User Interface page (Medsquare RDM) shows the tab used to define dose limits for master protocols. On the left side, the highlighted part represents CT examinations of the abdomen, which includes many protocol names used for this exam. The right side displays percentile statistical analysis of the data on total DLP available for the CT exam of this anatomic region. Just below, it can be seen the reference values set for Level 1 and Level 2 alerts for adult patients (default) and two age category groups for pediatric patients (Conditions (1): 0–4 years and Conditions (2): 5–15 years). It should be noted that the national DRL values were used for setting the thresholds for Level 1 alerts for each acquisition, while the double of the national DRL values were used for setting the threshold for Level 2 alerts.

calculations are reasonable [36]. This means that they should have access to the k-factor library, especially when this is preset by the DMS vendor, to check the k-factor values against values found in the literature. When elaborate methods and phantoms are used for E and organ dose calculations, such verification may be difficult since the average medical physicist may not have independent programs for such detailed calculations. However, some sampling or checking of DMS calculations against simple calculations using k-factors or easily accessible free software [25] can be used to assess any conspicuous errors.

2.2.2. Data analysis and alerts

One of the major uses of DMS is to facilitate the fulfilment of legal requirements, that is, to record the dose metrics and compare them with the respective Diagnostic Reference Levels (DRLs) determined for each CT examination type. These DRLs are established either from surveys in many installations or national dose repositories (such as American College of Radiology's Dose Index Registry [67]) and are commonly defined as the rounded third quartile value of the mean values of the respective dose metrics in the surveyed installations for standard sized adults and children of five age categories (0-, 1-, 5-, 10- and 15- years old) [68–71]. This means, that for each specific examination type, 75% of the surveyed installations had respectively, mean CTDI_{vol} and DLP values less than or equal to the respective DRLs, while 25% of the installations had mean values of dose metrics above DRLs. Since by

definition, the DRLs are reference values to serve as a guide to distinguish cases where dose metrics are above what is considered normal, the comparison of the dose metrics of a facility to the respective DRLs should not be done on a patient by patient basis. It is the median (rather than the mean which was initially used) values of dose metrics of a sample of patients which should be compared to DRLs, as the median is not affected by outlier values as much as the mean [72].

However, when it comes to dose alerts, these are based on comparison of the dose metrics values with respective reference values (which serve as thresholds), set for a whole exam and each acquisition series. This comparison is done on a patient by patient basis. In DMS usually there are two levels of alerts - low (usually denoted with an orange color mark) and high (usually denoted with a red color mark), which are posted when the dose metric values are higher than the thresholds set for each type of alerts. It must be stressed that the reference values are not preset; their selection is a responsibility of the DMS user which has the role of administrator and therefore has access to the basic configuration menu. Different alerts are defined for single phase and for multiphase examinations involving multiple acquisitions, as well as for each individual scan series within a multiphase examination. An example of a page showing all exams performed in one week in three CT scanners is given in Fig. 6.

Though the reference values for these alerts should be related to the DRLs, they are not the same thing. For example, the orange alert

Fig. 6. Graphics User Interface page (Medsquare RDM) shows the tab used to review all CTs performed on three scanners over a 1-week period. The green, orange and red colored round icons (in the third column: Alert Dose) denote that the total DLP values are below Level 1, between Level 1 and Level 2, and above Level 2 reference values, respectively. However, these symbols may denote that the respective reference values of any of the acquisitions within the exam has exceeded, or signify that the maximum number of acquisitions allowed for an examination has exceeded. The round icons with a warning symbol indicate examinations assigned to an anatomic region category automatically by the RDM (because the protocol names of these exams have not been assigned to a master protocol). The colored bar (5th column) may be shown as $\frac{1}{4}$ high blue colored, $< \frac{1}{2}$ high green colored, $> \frac{1}{2}$ high orange colored, or $\frac{3}{4}$ high red colored to denote if this exam is below the 25 percentile, equal or above the 25 percentile and below the 50 percentile, equal or above the 50 percentile and below the 75 percentile, or finally, equal or above the 75 percentile, respectively, compared to the other studies of the same region performed in the last 2 months. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

reference value for a single scan examination could be set equal to or slightly higher than the respective diagnostic reference level (DRL) values. This could be a good option, if the median values of all CT installations connected to the specific DMS are not too close to the DRLs. If the median value for any CT scanner is very close to DRL, then many orange-alerts would be produced for this CT scanner, for all patients who are simply larger than the average. This is because by definition, the median value of a distribution separates the sample in two halves; half of them are lower and half higher than the median. This means that, if an alert was set close to the median value of a metric, about half of the patients would produce an alert. In an optimal practice, for the same scan protocol and body region, thinner as well as shorter patients should have lower CTDI_{vol} and DLP values compared to obese and taller patients.

The selections of reference values can be a bigger issue for institutions with scanners from different generations and features since the newer scanners armed with efficient detectors and iterative reconstruction techniques can have much lower doses than older legacy scanners [73]. Thus, scanner specific threshold values, based on scanner capabilities, may be needed. Finally, it should be noted that special low dose protocols for some clinical indication, e.g. renal stone CT [74,75] and pulmonary nodule follow-up CT, should be distinguished from other protocols that share the same anatomic scan region, otherwise they will constantly produce low dose outliers.

In summary, choosing a low reference value for orange alerts, will lead to many orange alerts which may mean nothing and the DMS users may become accustomed to ignoring them, something which limits the usefulness of having the alert in the first place. On the other hand, if the alert reference value is set too high, then the opposite situation would prevail. The selection of the reference value of the red alert is even more important, because typically red alerts require some action by the side of the DMS user. The reference level for red alert should be set at a value high enough so that normally, it would be posted only for very

obese patients or/and when something is wrong (higher than necessary doses). Thus, the threshold for this alert could be set at a higher value e.g. double the DRLs. This is the rationale used for setting the red alerts (Level 2) in the example shown in Fig. 5.

Typically, an unresolved alert will stay active until the user uses the proper tool to justify it or verify it, e.g. by writing a comment. It is good practice for the DMS user to review at least once a week the list of patients in alert (usually containing only red alerts) and try to identify possible reasons which may be responsible for this alert. An alert may be caused by various reasons; it may be the patient size being too large, the scan length being too long, or it may be due to the modification of the typical protocol or its use for another type of examination than which was designated. Review of the scan settings and comparison with the ones typically used, will reveal any of these differences. DMS users may need to review the scan ranges, scan settings, and identify if a different examination type was performed compared to its classification in the DMS. An example of a “studies in alert” page is given in Fig. 7.

To address issue of how patient size affect and require different CTDI_{vol}, some studies have described size and/or age-based DRLs for both CTDI_{vol} and DLP [76,77]. Another dose metric that could be used for this purpose is SSDE which corrects CTDI_{vol} for patient size; for lean patients the SSDE values will be larger than CTDI_{vol} and for obese patients smaller. Therefore, using reference values for SSDE can help reduce the number of false alarms regarding CTDI_{vol}. However, this metric proposed by the AAPM is not as widely accepted or even displayed on scanner graphic user interface. Furthermore, as aforementioned, AAPM does not recommend use of SSDE for estimating DLP or E. Some DMS automatically estimate the patients’ cross-section diameters (such as anteroposterior, lateral or effective diameters) to estimate SSDE from CTDI_{vol}. These DMS can enable alerts based on SSDE rather than CTDI_{vol}. However, universal acceptance of SSDE is critical before their widespread use. Although specific to patient size, SSDE has several limitations such as use of abdominal size for chest CT, lack of

CR	CT	DX	MG	PT/CT	RF	XA	Alert Dose	E (mSv)	Total DLP (mGy.cm)	Total DLP 16 (mGy.cm)	Total DLP 32 (mGy.cm)	IR Events	DLP w/acq (mGy.cm)	CTDIvol w/acq (mGy)	Contrast Product	Patient ID	Patient Name	Sex	Pregnancy Status	Age	Weight	BMI	Procedure
								11.23	4681.00	4678.00	3.00	2	2339.00	99.37				M		77			CT Head
								28.26	1659.13		1659.13	1	1652.76	33.30	APPLIED			M		49	144	50.42	CT Abdomen and pelvi
								28.80	4288.96	4288.96		3	1584.31	57.31	None			M		45			CT Head
								47.16	2643.89		2643.89	3	1235.87	22.96				M		70			CT Thorax with contras
								54.39	4064.20	2508.57	1555.63	4	870.09	21.05				M		42			CT Abdomen and pelvi
								26.85	2635.30	2635.30		1	2632.31	78.89				M		55			CT Head
								34.69	2901.25	2291.18	610.07	3	795.28	21.47				M		41			CT Abdomen and pelvi
								41.24	3259.19	2292.41	966.78	3	947.72	24.01				M		119			CT Abdomen and pelvi
								37.80	2032.00		2032.00	1	1997.79	39.26	CE			M		74	85		CT Angiogram aorta
								62.93	3687.79		3687.79	4	1038.54	20.35	APPLIED			M		74			CT Angiogram pulmon

Fig. 7. Graphics User Interface page (Medsquare RDM) shows the tab used to review the studies in red alert for the total DLP value. The chessman icon in the left edge of the figure for most of these studies is blue and red for only three cases. The red chessman icon indicates that the patient is also at risk, because of exceeding the number of exams that can be performed within a period of time or/and the accumulated dose in the same period (as set by the DMS administrator) have been also exceeded. This particular DMS has a tab for analyzing those cases also. The red colored light icons (third column) appear in two different icon versions; with the warning symbol (the exam was automatically assigned by the RDM to an anatomic region category) and without it (the examination protocol has been assigned by the administrator to an anatomic region category). If a comment is added to these studies, meaning they have been reviewed, a green checkmark symbol will appear instead of the warning symbol. The red BMI value on the right (2nd row) signifies a very obese patient. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

application to other body parts like neck or legs, and lack of accountability of different patient attenuation (muscle vs fat).

2.2.3. Statistical analysis and reports

All DMS systems offer tools for statistical analysis of data and presentation of the results in reports using summary tables and graphs. Users can select one of the preset dashboards or create new ones according to their needs. A dashboard can display dose information with a combination of tables and graphs of various formats (column, scatter or pie charts) over specified time intervals (e.g. one day, one week, one month).

Dose information can be displayed and summarized in tables and graphs on the minimum and maximum values in the sample, mean, median, standard deviation and quartile values, and also reference values for alerts. Graphs can help plot dose values with lines to show several statistics including median and third quartile values or alert levels on the frequency graph. The user may select to depict the same information for a specific examination protocol and compare the distributions of two or more CT scanners or select a single CT scanner and compare the dose metric distributions of many different examination protocols or select those with the highest dose metrics. The possible selections are too many to mention but some typical examples of statistical reports are shown in Figs. 8 and 9. The DMS user can also select specific columns or data points in a graph (e.g. high or low dose outliers) and review the relevant exam data, one by one. Finally, some DMS can display and analyze features such as scan length, E , organ doses, or SSDE data distributions, as well as scan parameters such as kV, mA, collimation, pitch etc. so that cases where the acquisition parameters are different than those stored in the protocol can be identified.

For multiphase examinations, both series level DLP and the total value of DLP (sum of all series DLP values) can be assessed. For CTDI_{vol} however, adding the individual values is obviously wrong, while an average or individual value, though probably more reasonable, is of limited use. To account for multiphase examinations, some DMS

calculate some other surrogate metrics using the CTDI_{vol}, SSDE and DLP of individual scan series of the examination. In a DMS the indices CTDI_{vol} w/acq and DLP w/acq are calculated (where w/acq stands for weighted by acquisition), as the average values per acquisition for each examination. The metrics of each series are multiplied by the respective scan lengths and their sum is divided by the scan length sum [37]. In another DMS [78], a similar rationale is used for calculating scan length-weighted CTDI_{vol,sw} SSDE_{sw} surrogate metrics.

However, as has been noted by Li et al. [78], both CTDI_{vol} and SSDE were originally developed for indicating the average dose over the central scan plane of the CTDI phantom or the patient for a single scan series performed with constant mA, and are not intended for the dose associated with multi-series and ATCM acquisitions. Li et al. [78] pointed out, that according to the AAPM TG111 report [23], the dose at the scan center of a scan series increases with scan length, due to the increased scatter contribution. While this explains in part the reason for using scan weighted dose metric surrogates, as commented by Li et al. [78] these metrics or their sum, conveys no meaningful information. Instead, Li et al. [78] proposed a method for the calculation of dose profile sums along the scan axis (z-axis) and suggested that its incorporation in DMS would provide a more meaningful metric and would enable the calculation of the Z-axis position where the maximum dose occurs. The rationale of their method is on the same page as that used in GE CT scanners for calculating the “max Z location CTDI_{vol}” [79], which is the maximum value of the summation of CTDI_{vol} in the overlapping ranges of multiple scans. As aforementioned [6,11] this metric may be used for a crude estimation of skin dose, to alert the user for the possibility of deterministic effects occurrence.

2.2.4. Limitations and warnings

DMS gather data from CT scanners and other X-ray units and they process these data to derive more patient dose related metrics like E , organ doses and other risk estimates. Derivation of patient-specific E and organ doses from CT output doses (CTDI_{vol} and DLP) can lead to

Fig. 8. Graphics User Interface page (Medsquare RDM) shows the tab used to statistically analyze the dose data of all procedures performed in a single CT scanner for a period of 2 weeks. The left side shows a histogram of the DLP w/acq data (which is the metric highlighted below the histogram). The two vertical dashed lines in the histogram denote the median and third percentile value of the data included. On the right side a full statistical analysis of all dose related metrics is given in a tabular form.

erroneous estimations. The user must be aware that these derived metrics are only as accurate as the methods that have been used to produce them. Even if the most evolved 3D anthropomorphic phantom has been used, the values for effective and organ doses are just estimates and should be used as such. Many DMS do not explicitly state the exact method used for calculating E and organ doses from the DICOM image data. Therefore, users must employ $CTDI_{vol}$ and DLP to compare doses

across different scan protocols and scanners.

Setting up correctly the DMS by its manufacturer is of paramount importance, because it must be made certain that every specific parameter needed by the DMS for calculation or reporting purposes, is extracted from the correct DICOM tags or the RDSR and that all data are validated. This may be cumbersome and in some cases an impossible task, as different manufacturers do not use the same tags for all

Fig. 9. Graphics User Interface screen capture from a radiation dose monitoring software (Radimetrics™ Radiation Dose Management Solution, Bayer Inc.) shows a bar diagram of number of exams per CT scanner at the Massachusetts General Hospital (MGH) with radiation doses below the set threshold. Radiation doses for all scanners except the one coded as CT3B2 were below the set threshold (below the ACR recommended DRLs). For CT3B2, 2% CT exams were above the dose threshold and had to be individually analyzed.

parameters, some may be mentioned in vendor specific fields, and for some parameters, some manufacturers may not report the value in any DICOM tag or in RDSR, where formats may also vary.

Proper configuration of the DMS by the user with administrative rights, is also of paramount importance because its choices may severely affect the accuracy and reliability of the reported results and severely limit the benefits expected using the DMS. Probably the most important thing is the correct categorization of examinations, since otherwise statistical analysis results may be corrupted and misleading. However, for successful categorization of the examinations there must be a consensus in all departments and radiological centers connected to the DMS that for each specific examination, specific only protocols are used, and this is done consistently. In that case the task is made considerably easier and occasional errors cannot skew the big picture, except of occasionally producing outliers.

Another limitation of the DMS is the need for busy imaging practices to put in substantial initial effort to create a system of harmonizing or the very least mapping of different protocol names and body region, and training of CT technologists to use body region and clinical indication specific protocols. Unless the department and/or hospital designate and mandate personnel to periodically monitor alerts at a frequent time-bound fashion and take action on protocols with quality or high-dose issues, DMS can become relegated to one more of the umpteen unused and redundant software in busy healthcare practices. Any monitoring exercise should be associated with a recorded and auditable trail. Unfortunately, few DMS allow users to enter notes or explanations to address identified alerts or issues; as a result, users have to use alternate means of maintaining a “paper-trail” of their monitoring. An example of investigation of high dose cases is shown in Fig. 10.

Another limitation of DMS is the need to map new scanner information each time the hospital replaces or acquires a scanner. Often scan protocols cannot be transferred from older to newer scanners or across different scanner vendors. This creates opportunities for errors with manual entry of scan protocols which can result in issues with the DMS.

Finally, DMS is not a be-all and end-all for CT dose optimization, especially if clinical indication or need for CT is not justified and regulated. Adoption of DMS does not absolve imaging sites from the responsibility of ensuring that each CT and acquired scan series are justified. Since when not justified, even a low-dose CT is a high-dose exam!

2.3. Dose monitoring systems as optimization tools

DMS have been used for many years now, especially for CT installations, and from the experience gained so far it is obvious that they are powerful tools in the quest of optimization. A large amount of experience on the use and the benefits of such systems was gained by the American College of Radiology (ACR) Dose Index Registry (DIR) which is operating since 2011 [67,76,80,81]. According to the information found in its website (<https://www.acr.org/Practice-Management-Quality-Informatics/Registries/Dose-Index-Registry>), as of April 2018 there were 2100 facilities connected to the DIR, with more than 50 million exams collected. Exam data are transmitted to the DIR automatically from DMS and/or CT scanners (after anonymization at the site). To assure that data are comparable across facilities and scanners, the exam descriptions are standardized, using RadLex Playbook [82]. Patients are divided into adults and five age groups of paediatric patients. In addition to CTDI_{vol} and DLP, for body examinations the DIR also computes SSDE. Each facility receives a report where the data from all facilities are reported in a box-and-whisker plot, where the data (min, 1st quartile, median, mean, 3rd quartile and maximum values) of all installations are reported, including a mark to show the participant's position relative to this distribution. An example of such a report is shown in Fig. 11. Among the accomplishments of the DIR, in co-operation with the ACR, was the development of size-specific DRLs and Achievable Dose guidelines for the 10 most common adult CT examinations [76]. DIR has increased awareness of radiologists regarding patient dose issues and has prepared the way for other countries which would like to create their own national dose index registry.

To our knowledge, a Dose Index Registry so extended as that of the ACR doesn't exist in any other country of the world. However, similar attempts, though in a smaller scale, have started in other countries as well. For example in Italy, 13 centers having a common DMS (Radiation Dose Monitor, Medsquare, France), collected and analyzed data from 19 CT scanners. Feedback reports, were provided to each of these centers, regarding its performance, in terms of the CTDI_{vol}, in comparison to the overall distributions and against other participants [37].

The DMS can serve as an optimization tool, whether they are stand-alone in a single institution or they are connected in a large network of installations, like the ACR DIR. In both cases the main goal is common: to avoid unnecessarily high doses, and when necessary, to reduce doses. In some cases, DMS can also help identify protocols with inadvertently low doses without sufficient image quality; such protocols may require an increase in doses. Adjustment in radiation doses must be done without compromising the diagnostic confidence, i.e. to determine the “right” dose for each case which is patient size, diagnostic task and CT

Scanner	CTDI _{vol}	DLP	Comments	Action
CT2W1	99.0	1969.5	CT Software Glitch	Education/ Ensure to have lateral topogram without cutoff
CT2W1	95.1	2005.7	Bariatric patients	N/A
CT2W1	109.4	3617.8	Large shoulders in the topogram	Consider to use fixed technique for head
CT1Y6	105.4	1024.6		Further review.
CT2B2	95.1	1785.0	Used fixed technique	Should use AEC
CT1NS	83.6	3613.1	Fixed technique too high	Lower the fixed technique
CT2W1	94.6	2023.2	Large shoulders in the topogram	Consider to use fixed technique for head
CT1WA2	89.0	3686.2	Tabletop head, scout with arms, AEC	Should used fixed technique, Education
CT2W1	115.1	3851.8	Patient moved after topogram	Education/ retopo after patient being moved

Fig. 10. At the Massachusetts General Hospital (MGH), data on CT exams from DMS software (Bayer Inc. Radimetrics xExposure) above the set threshold levels are exported to a Microsoft Excel file and reviewed periodically by a team of medical physicists and CT Quality Assurance manager (a certified CT technologist). Each exam with higher doses is reviewed to define the reasons for higher doses and document mitigating actions. The yellow highlighted row implies need for further investigation. For this specific case it was later found to be a head CT scanned with automatic exposure control (AEC). The patient's large shoulders projected in the field of view and resulted in higher than needed doses. To avoid excess doses, it was decided to use fixed mA technique for head CT when large shoulder or arms cannot be optimally positioned outside the field of view due to patient discomfort or morphology. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 11. The biannual ACR Dose Index Registry (ACR DIR) report on CT radiation dose metrics (CTDI_{vol}, DLP and SSDE per exam) for the top 10 CT protocols at Massachusetts General Hospital (MGH). The box and whisker plots depict median MGH doses plotted against radiation doses from other contributing CT sites in the United States. Most median doses at MGH (red lines) were below the median or the 25th percentile of the national doses. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

scanner technology dependent. However, in the case where DMS systems are connected in a large network, the analysis of data collected from many systems of the same vendor and model, can make the aforementioned task easier, since personal preferences and convictions of one radiologist face these of his/her other colleagues. For example, it is rather difficult for one not to question the reason why he/she needs 2 or 3 times the dose that others need to perform the same diagnostic task using the same equipment.

2.4. Dose monitoring systems: Special features and future applications

Though DMS mostly deal with dose related information, they can practically be used to collect any other information contained within RDSR or DICOM data, regardless whether this information was typed by the user (e.g. in a comment field like patient weight) or it was automatically created by the CT scanner. Therefore, the DMS can also record data concerning the contrast media quantity injected. Some DMS are integrated with the contrast injectors and automatically acquire the contrast injection volume and rates, while others do not communicate with the contrast injector interface, and therefore, do not include contrast injection details. While not related to radiation risk, monitoring of contrast media quantity can be important for cost reimbursement as well as maintaining a record of injected contrast media into individual patient and scan protocol. Newer and faster CT scanners can allow use of lower contrast media volume at lower radiation dose as compared to older scanners which are slower and need a higher kV due to low x-ray tube power. A single interface or program that enables simultaneous dose and contrast media volume use can allow such comparison. Furthermore, a quantity of contrast media larger than appropriate, may increase artifacts and result in a reduced image quality.

Another special feature that some DMS systems offer is software for mapping the dose to the skin entrance surface and calculate the peak skin dose, which however at present is limited only to fluoroscopically guided interventional procedures. Peak skin dose is important when it

comes to the deterministic effects of radiation, as skin doses above certain threshold values are expected to produce certain radiation injuries. Since CT scanners are also used for interventional procedures, where it is known that skin doses may become very high [83–85], while in some cases interventional procedures may be repeated many times [86], it is expected that in the future DMS may provide features for skin dose mapping and peak skin dose calculation in CT. This is because according to ICRP Publication 85 [87], when the maximum cumulative absorbed dose in skin for an actual procedure appears to approach, equal or exceed 1 Gy for procedures that may be repeated and 3 Gy for any individual procedure, it should be recorded in the patient record, along with the location and extent of the skin site.

Concerning the future of DMS, it is expected that DMS will gradually integrate all imaging modalities. As DMS are primarily used for patient dose monitoring, a future application may be patient specific dosimetry; using patient specific segmented models (created by the CT examination images) and Monte Carlo algorithms detailed information on organ doses and related cancer risk estimates could be provided for each specific patient [58,88]. However, future applications of DMS may extend far beyond dose metrics. Some DMS already offer features to assist with repeated exams and reject analysis of X-ray images. DMS can be used to keep track of all examinations performed on the same patient and update his or her dosimetric record [89,90]. Workload calculation is another example, which could be useful for maintenance, shielding and staff radiation protection evaluation purposes. Another field where DMS could be of service is the evaluation of image quality. Routines that could automatically quantify the noise levels or contrast-to-noise-ratio of clinical images, could be useful assure that image quality is maintained and in conjunction with dose levels could further assist in protocol optimization. Another possible application of DMS, possibly in connection to another system for clinical decision support, could be the justification of the radiological exams in relation to clinical indication [91] which could address issues like the possible overutilization of CT [92]. Given the fact that DMS networks like ACR DIR, are essentially huge examination and dose data banks, they could also help in

Table 1

A list of some commercially available DMS systems and link to the relevant websites.

Company	Product	Website
Agfa Healthcare	Enterprise Dose Management (powered by DoseMonitor)	https://global.agfahealthcare.com/main/enterprise-imaging/dose-monitoring/
Bayer Healthcare LLC	Radimetrics Enterprise Platform	https://www.radiologysolutions.bayer.com/products/dosing-software/radiation-dose-management
Bracco Diagnostics	NEXO[DOSE]	https://imaging.bracco.com/us-en/products/injectors-informatics/nexo-dose
Fujifilm Medical Systems U.S.A., Inc.	Syncro-Dose	https://www.fujifilm.eu/uk/products/medical-systems/solutions/medicalinformatics/syncro-dose
GE Healthcare	DoseWatch	https://www.gehealthcare.com/products/dose-management/dosewatch-dose-monitoring-software-ge-healthcare
GE Healthcare	DoseWatch Explore	https://www.gehealthcare.com/products/dose-management/dosewatch-explore
Guerbet LLC	Dose&Care	https://www.guerbet.com/products-solutions/digital-solutions/dose-care/
Medic Vision Imaging Solutions Ltd.	SafeCT	https://medicvision.com/usa/products/safect
Medic Vision Imaging Solutions Ltd.	SafeCT-29	https://medicvision.com/usa/products/safect29
Medsquare	Radiation Dose Monitor (RDM)	https://www.medsquare.com/en/radiation-dose-management/
Philips	DoseWise Portal	https://www.usa.philips.com/healthcare/clinical-solutions/dosewise
Qaelum	DOSE	https://qaelum.com/highlights-video-qaelum-radiation-dose-management-solution
Sectra Inc.	Sectra DoseTrack	https://sectra.com/medical/product/sectra-dosetrack/
Siemens Healthineers	Teamplay dose	https://www.siemens-healthineers.com/digital-health-solutions/digital-solutions-overview/service-line-management-solutions/teamplay/teamplay-performance-management-applications/teamplay-dose
SSTgroup inc.	Radiation Dose Monitor	https://www.sstgroup-inc.com/radiation-dose-monitor/

conducting large scale epidemiological studies regarding radiogenic cancer risk analysis, provided that cancer incidence data banks (e.g. from oncologic departments) can be linked to DMS. Links to commercially available DMS websites can be found in Table 1.

2.5. Role of imaging personnel in DMS

Protocol and radiation dose optimization require a teamwork in which medical physicists, CT technologists, and radiologists, cardiologists or any physicians are involved in specialized CT exams, must participate as partners. Qualified medical physicists are perhaps the most suitable personnel for primary responsibility of DMS. Medical physicists carry most of the initial burden of setting up the system and validating data transfer, E, organ dose and SSDE calculations, k-factors, DRL and alert level settings etc., and therefore should be assigned with administrator privileges [36]. They must work with CT technologists and/or radiologists when dose outliers are identified so that protocol adjustment can be undertaken while maintaining diagnostic information. CT technologists also play a crucial role in dose optimization since their help in standardization of protocol and scan series nomenclature is a key pre-requisite to obtaining analyzable dose data. Radiologists with understanding of CT scan protocols can also serve as administrators for allocating new examination protocols to the correct category. Last but not least, radiologists must support and participate in dose optimization efforts with an open mind since *primum non nocere* is a collective responsibility of all physicians, and DMS facilitates this key premise of medicine in radiology departments.

3. Conclusions

In summary, dose monitoring systems play an important role in dose monitoring and optimization in radiology departments [93,94]. They help evaluate imaging protocols and radiation doses, obtain information on dose outliers, and monitor the effect of protocol adjustment. Despite the ease of data capture, analyses and display with systems, they require a constant commitment to obtain meaningful data for complex protocols and mitigate identified dose and image quality issues.

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