Imaging dose in variable pitch body perfusion CT scans: An analysis using TG111 formalism

Marian Axente and Dimitre Hristov
Department of Radiation Oncology, Stanford University Medical Center, Stanford, California 94305-5847

(Received 4 September 2013; revised 15 April 2014; accepted for publication 27 April 2014; published 21 May 2014)

Purpose: To investigate the variation of imaging dose with tube potential in variable pitch body CT perfusion (CTp) protocols using the TG111 dosimetric formalism.

Methods: TG111 recommendations were followed in choosing the phantom, dosimetric equipment, and methodology. Specifically, equilibrium doses ($D_{eq}$) were measured centrally and peripherally in a long PMMA phantom. Reference planar average equilibrium doses were determined for each tube potential, for a reference set of exposure parameters (collimation, pitch, filtration) on a Siemens Definition CT scanner. These reference values were utilized to predict the imaging dose during perfusion scans using interpretations of the TG111 formalism. As a gold reference, the midscan average planar perfusion doses ($D_{CTp}$) were obtained directly from central and peripheral $D_{eq}$ measurements for body CTP scans (144 and 271 mm) using variable pitch acquisition. Measurement-based $D_{CTp}$ values obtained using a thimble chamber were compared to the TG111-predicted values, and to CTDI$_{vol}$ reported at the console.

Results: Reference planar average equilibrium dose values measured for reference uniform pitch helical scans were consistently higher than console-reported or measured values for CTDI$_{vol}$. The measurement-based perfusion dose $D_{CTp}$ was predicted accurately by the reported CTDI$_{vol}$ for the 144 mm scan. The 271 mm scans delivered systematically larger dose than reported. The TG111-based dose estimates were proven to be conservative, as they were systematically higher than both the measured and the reported imaging doses.

Conclusions: Upon successful implementation of TG111 formalism, standard imaging dose was measured for a body CTp protocol using the variable pitch helical acquisition. The TG111 formalism is not directly applicable to this type of acquisition. Measurement of dose for all variable pitch protocols is strongly suggested. © 2014 American Association of Physicists in Medicine.

Key words: CT dose, TG111, perfusion CT, shuttle mode, variable pitch

1. INTRODUCTION

Depicting vascular physiology in addition to detailed anatomy, perfusion computed tomography (CTp) imaging is clinically attractive to oncology applications where exact perfusion quantification could provide important functional data about tumor presence, aggressiveness, and viability throughout the treatment course.

The Adaptive 4D Spiral (shuttle) mode available on the SOMATOM Definition AS+ scanners (Siemens Medical Solutions, Malvern, PA) is a novel CT perfusion technique that employs variable pitch continuous projection acquisition with table bidirectional motion (in and out of the gantry) during contrast agent diffusion. Per the State of California Health and Safety Code, hospitals running CT installations are required to add the imaging dose to the patient record. For each patient, the acquisition software appends representative CTDI and DLP values for each acquired imaging study. However, it has been indicated that CTDI-based metrics may underestimate dose in uniform pitch helical scans that employ extended ranges and/or large collimations, which is the case in body perfusion scans. Furthermore, the nonuniform table velocity used in the shuttle mode adds complexity to the dose estimate.

Following accounted cases of patient overexposure of brain CTp, FDA has raised attention to this type of dynamic imaging making recommendations about potential dose limits. Furthermore, AAPM has published actual acquisition parameters that could be utilized for safe image acquisition of brain perfusion data for mainstream CT equipment. However, there are no similar indications for body CTp, neither for uniform pitch nor for shuttle mode acquisitions. Therefore, there is a practical need for reference data for future clinical implementation of these useful imaging protocols. In this paper we measure imaging dose reference data for helical scans acquisition utilizing a newly proposed dosimetric formalism (AAPM Task Group 111). Using these data, the CT dose for body CTp scans is calculated and compared to the reported and measured dose during these protocols. As various dose estimates and measurements are presented, Table I summarizes the notations for the ones most commonly referred to in the paper.

2. MATERIALS AND METHODS

2.A. Scanner configuration and perfusion protocols

All images and dose measurements were acquired on a Siemens SOMATOM Definition AS+ scanner. This scanner

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061912-1 Med. Phys. 41 (6), June 2014 © 2014 Am. Assoc. Phys. Med. 061912-1
allows a maximum of 128 simultaneously acquired slices with a maximum detector array axial coverage of 38.4 mm (for helical scans). The maximum continuous scan time is 100 s, the selectable uniform pitch ranges from 0.35 to 1.5. A low tube voltage (70 kVp) is available besides the regular Siemens options (80, 100, 120, and 140 kVp).

The body perfusion protocols implemented on the scanner allow for static table acquisition or continuous helical acquisition in shuttle mode for extended scan ranges. The longer available scan lengths for variable pitch perfusion scans vary between 144 mm (1.5 s per scan) and 271 mm (2.5 s per scan). The Siemens tube voltage (CARE kV) and tube current modulation (CARE Dose 4D) are disabled for these protocols, while the collimation remains constant during the acquisition. For the available collimation, there are two acquisition settings available for these protocols: standard 32 channels (32 × 1.2 mm) and the 64 channels acquisition (64 × 0.6 mm). As a default setting, the shortest tube rotation period (0.3 s) is utilized for these scans. The “adaptive” nomenclature refers to the fact that multiple scan ranges as well as different temporal sampling schemes are available for the end user to set.

2.B. TG-111 dosimetric formalism

The TG111 formalism introduces the equilibrium dose ($D_{eq}$) as the basic metric for reporting imaging dose. $D_{eq}$ is defined as the cumulative dose at the center of a scan of infinite length, similar to CTDI. In CTDI-based dosimetry, the imaging dose for a helical scan of arbitrary collimation and pitch is approximated from measurements done with the phantom and table held stationary (axial acquisition). Based on measurements acquired with standard 10 cm pencil chambers, CTDI metrics underestimate the dose deposited by scattered photons for collimation larger than or scanning ranges beyond the active length of the chamber. Unlike CTDI formalisms, TG111 methodology employs direct measurement of the equilibrium dose during helical scans using a small ion chamber located at the center of a phantom of uniform cross section and composition, long enough so that the contribution of sources of scatter radiation at the phantom edges to the central measuring point is minimized. In the presented study, the phantom used for TG111 measurements is composed of three 32 cm diameter CT dose PMMA phantom model 007A (Computerized Imaging Reference Systems, Inc., Norfolk, VA), linked together for 45 cm total length. The 23 mm active length, 0.6 cm$^3$ Farmer chamber (PTW TN 30013, Freiburg, Germany) was calibrated by an accredited dosimetry calibration laboratory (ADCL) for two diagnostic beam qualities (80 and 120 kVp). The phantom–chamber system was placed on top of the carbon fiber couch top, aligned with its long axis to the scanner rotation axis using lasers within 1 mm/1° uncertainty (data not shown), and then translated through the beam plane during image acquisition, such that the chamber acquired symmetrical readings on both sides of the beam plane. The acquisition pitch for the measurements ($\rho_{ref} = 0.5$) was selected such that it allowed for integrating charge over at least two tube rotations, minimizing oscillations in the readings, especially for peripheral dose measurements.

2.C. Dose variation with tube potential

Specifically for uniform pitch helical scans, the reference planar average equilibrium doses ($D_{eq,ref}$) were determined for each tube potential as per TG111 recommendations: the cumulative central and peripheral doses were measured for a set of scanning lengths ranging from 5 cm to phantom length minus $nT$ for a reference set of exposure parameters that are commonly used for body CTP ($nT = 32 	imes 1.2$ mm collimation, standard adult filter) and $\rho_{ref}$. The integrated charge from all scans was corrected for environmental conditions and transformed into dose (air kerma) using the available calibration factors. The doses were fitted as a product of the $D_{eq}$ and the “approach-to-equilibrium” function: $h(L) = 1 - \alpha \cdot \exp(-4L/L_{eq})$, where $\alpha$ is a fitting parameter related to the scatter-to-primary ratio, $L$ is the scanning length defined as the ratio of the displayed DLP and CTDIvol, and $L_{eq}$ is the minimum distance at which scatter equilibrium is achieved at the point of measurement. The $D_{eq,ref}$ was calculated as a weighted sum of the central and peripheral axes equilibrium doses and compared to the measured console values for CTDIvol. For comparison consistency, the regular weighting (1/3 central, 2/3 peripheral) was utilized rather than the TG111 suggested equal weighting. While using equal weighting for the central and peripheral readings would reduce the observed differences between planar average $D_{eq}$ and CTDIvol, measurements have shown that the regular weighting scheme is more accurate than the TG111 proposed one when it comes to predicting the planar integral dose.

It has been demonstrated that for a given collimation, tube potential, and filtration, the product of equilibrium dose and pitch remains constant. Therefore, in order to calculate an estimate of the imaging dose during body CTP using the acquired reference data, the average planar $D_{eq,ref}$ measured for the reference conditions (32 × 1.2 mm collimation, standard adult filter, 0.5 pitch) needs to be scaled by the pitch ratio. However, the shuttle mode employs a variable pitch with the table moving in and out of the gantry. In order to evaluate how accurate are the doses displayed at the console and recorded in the patient record, different methods to estimate the pla-
narrow average dose were devised for perfusion scans, utilizing adaptations of the TG111 formalism.

In addition, the CTDI100 values were measured directly for the collimation used in the reference scans, with an ADCL calibrated 10 cm pencil chamber (PTW TN 30009, Freiburg, Germany) in the standard CT body phantom using the TG66 formalism\(^\text{11}\) for the given reference exposure parameters, to detect any systematic differences between the console reported CTDI\(_{\text{vol}}\) values and the scanner output. Corresponding CTDI\(_{\text{eq}}\) and CTDI\(_{\text{vol}}\) were calculated based on accepted formalisms.\(^8\)

2.C.1. Planar average dose measurement for body perfusion scans

The midscan planar average imaging dose during the perfusion scan was determined from measurements using the TG111 experimental setup described above for the 144 and 271 mm body CT\(_p\) protocols (32 × 1.2 mm, standard filter), for all tube potential values. This quantity is denoted as \(D_{\text{CTp}}\). For 100 kV, \(D_{\text{CTp}}\) was determined for an increasing number of passes (from 1 to 30), to evaluate the linearity of dose accumulation for both acquisition protocols.

2.C.2. TG111-based calculation

The midscan planar average imaging dose during the perfusion scan was also calculated from \(D_{\text{eq,ref}}\) using interpretations of the TG111 formalism, and generally denoted as \(D_{\text{CTp}}^{\text{TG}}\). To characterize the imaging dose during variable pitch acquisition, the table motion curve was directly measured using a trakStar device (Ascension Technology Corporation, Vermont, CT) with midrange transmitter and Model 180 sensor, with a sampling frequency of 30 Hz over ten scans (table motion curves were not available from the manufacturer). In Fig. 1 the recorded average motion amplitude is presented as a function of time for one 144 mm body CT\(_p\) scan. The trakStar signal was highly reproducible. The absolute value of the mean deviation from the average motion curve over the ten passes was 1.9 mm. The raw table velocity curve was determined as a first derivative of the average motion curve.

The pitch variation as a function of time during each pass of the table was calculated based on the raw table velocity curve. To eliminate some of the noise in the acquisition of the table motion data, a model of the pitch as a function of time was created using a sum of sines fit (Matlab R2012a, Mathworks). Both the raw data and the fitted curves are shown in Fig. 1. Using these data, an average pitch (\(p_{\text{ave}}\)) can be calculated by introducing an instantaneous, time-dependent pitch \(p(t)\). Then, using the TG111 equilibrium dose pitch product constancy, the \(D_{\text{CTp}}^{\text{TG}}\) can be derived as a function of \(p_{\text{ave}}\):

\[
p(t) = \frac{\nu(t) \tau}{nT},
\]

\[
N_{\text{ave}} = \frac{\tau}{nT} \cdot \int_{t_{\text{ON}}}^{t_{\text{ON}}} \nu(t) \, dt,
\]

\[
D_{\text{CTp}}^{\text{TG}}(p_{\text{ave}}) = \frac{p_{\text{ave}} \cdot D_{\text{eq,ref}}}{p_{\text{ave}}}
\]

All parameters are defined as in TG111: \(b\) for helical scanning is the scan interval in mm, and is defined by the product between the uniform table velocity \(\nu\) and the tube rotation period \(\tau\). \(t_{\text{ON}}\) is the total beam on time. However, in body CT\(_p\) scans the table velocity is a function of time; therefore \(p_{\text{ave}}\) and correspondingly \(D_{\text{CTp}}^{\text{TG}}(p_{\text{ave}})\) were calculated as shown in Eq. (3).

The \(D_{\text{CTp}}^{\text{TG}}\) can also be estimated as an average planar dose which, if delivered uniformly over the scanned region, will result in the total absorbed energy deposited by the variable pitch scan. Thus

\[
E_{\text{tot}} = \rho \pi R^2 L D_{\text{CTp}}^{\text{TG}},
\]

where \(\rho\) represents the density and \(R\) is the radius of the phantom, \(D_{\text{CTp}}^{\text{TG}}\) is the planar average dose during the perfusion scan of scan length \(L\), and \(E_{\text{tot}}\) is the total absorbed energy. For a scan of arbitrary (including subequilibrium) length \(l\) and a given pitch,\(^7\) the total energy deposited is given as

\[
E_{\text{tot}} = \rho \pi R^2 L D_{\text{eq}}.
\]

For a variable pitch scan, the planar average equilibrium dose becomes a function of pitch, which in turn is a function of position during the scan. The deposited energy is

\[
E_{\text{tot}} = \int_0^L D_{\text{eq}}(p(l)) \, dl
\]

\[
= \rho \pi R^2 \int_0^{t_{\text{ON}}} D_{\text{eq}}(p(t)) \cdot \nu(t) \, dt
\]

\[
= \rho \pi R^2 \int_0^{t_{\text{ON}}} \frac{p_{\text{ave}} \cdot D_{\text{eq,ref}}}{p(t)} \cdot \nu(t) \, dt.
\]
TABLE II. Fitted values for central $D_{eq,c}$ and peripheral $D_{eq,p}$ equilibrium doses and corresponding $D_{eq,ref}$ values (mGy/100 mAs) from measured data for the reference acquisition technique.

| Tube potential | 70 kVp | 80 kVp | 100 kVp | 120 kVp | 140 kVp |
|---------------|--------|--------|--------|--------|--------|
| $D_{eq,c}$    | 1.7    | 3.3    | 7.9    | 14.0   | 21.9   |
| $D_{eq,p}$    | 2.9    | 5.0    | 10.7   | 17.9   | 26.3   |
| $D_{eq,ref}$  | 2.5    | 4.4    | 9.8    | 16.6   | 24.8   |

Using Eq. (2) definition of time-dependent pitch, Eq. (5) can be re-written as

$$ E_{tot} = p_{ref} \cdot D_{eq,ref} \cdot \frac{nT}{\tau} \cdot \int_{0}^{t_{ON}} dt = \left( nT \cdot \frac{t_{ON}}{\tau} \right) \cdot p_{ref} \cdot D_{eq,ref}. $$

(6)

Therefore, by combining Eqs. (4) and (6), $D_{CTP}^{TG}$ can be estimated as

$$ D_{CTP}^{TG} (E_{tot}) = \left( \frac{nT}{L} \cdot \frac{t_{ON}}{\tau} \right) \cdot p_{ref} \cdot D_{eq,ref}. $$

(7)

Equation (7) could be further reduced to a simpler form similar to Eq. (3). However, the average pitch that would be estimated from Eq. (7) is not equivalent with the measured $p_{ave}$. This is because for Eq. (7), the average pitch is calculated based on the actual scan length, as defined by the ratio between the displayed DLP and CTDI$_{vol}$ including the overscan region at the end of the set scanning region, while $p_{ave}$ is directly calculated from the table motion, which as seen from Fig. 1, is shorter than the actual exposed length (the overscan region is included in the reported scan length). Both estimates were compared against the console reported CTDI$_{vol}$ and the measured $D_{CTP}^{M}$.

2.C.3. Scanner reported CTDI$_{vol}$

The value for CTDI$_{vol}$ for helical scans is calculated based on Eq. (8):

$$ CTDI_{vol} = \frac{1}{p} \cdot CTDI_{w}. $$

(8)

Since the integral energy (or DLP) of a scan is independent of pitch for given mAs, the DLP of the Adaptive 4D Spiral acquisition is set to be identical to the DLP of a scan with the same collimation, scan time, but no table motion (axial acquisition for one table position). Then the CTDI$_{vol}$ reported by the scanner console for Adaptive 4D Spiral acquisitions is calculated as

$$ CTDI_{vol} = \frac{DLP_{axial}}{L} = \frac{CTDI_{w} \cdot nT}{L}. $$

(9)

where $L$ represent the table travel plus the detector width.12

3. RESULTS

3.A. TG111 formalism measurements with constant pitch

Multiple charge measurements were acquired for each scanning length, and the average value was utilized for determination of $D_{eq}$, for both central and peripheral measurement locations. The fitted $D_{eq}$ value and corresponding calculated planar average $D_{eq,ref}$ are presented in Table II. In Fig. 2, for each scanning length the measured dose was plotted for each tube voltage as to represent the accumulated dose per 100 mAs at the central and peripheral locations.

Acquired data fit other published data as presented in Fig. 3.
Fig. 3. Central axis dose measurements normalized to $D_{eq}$ for the 120 kVp scan. Solid black circles—current study data. Data extracted from published graphs (Refs. 4 and 13) for GE LS-16 scanner at 120 kVp using: open circles—$nT = 40$ mm; crosses—measured data for $nT = 20$ mm.

3.B. Comparison between CTDI$_{vol}$ and average planar dose for a finite length uniform pitch helical scans

Since CTDI$_{vol}$ and average planar dose based on a scan length of 100 mm represent the same dosimetric concept, direct comparison between these quantities for the same acquired scans is indicative of the difference or lack thereof between the two formalisms. In Fig. 4, the imaging planar average dose $D_{11.2 \, cm}$ for a “finite” scan length $L = 11.2$ cm was calculated from the approach-to-equilibrium functions for the central and peripheral location. The selected scan length defined as $L = \text{DLP}/\text{CTDI}_{vol}$ was the closest to the 10 cm active length of the standard pencil chamber used in CTDI$_{100}$ measurements.

Fig. 4. Variation of imaging dose with tube potential. Siemens reported CTDI$_{vol}$—values recorded from the console. Measurement-based CTDI$_{vol}$—values calculated based on CTDI$_{100}$ values measured on-site using TG66 formalism (12 o’clock position for peripheral measurement).

3.C. Comparison between CTDI$_{vol}$ and average planar equilibrium dose—Shuttle mode perfusion scans

The planar average dose was determined from measured central and peripheral $D_{eq}$ for the 144 and 271 mm body CTp scans using shuttle mode for all tube potentials, and it was compared to all TG111 estimates and the reported CTDI$_{vol}$ values (Table III). The accumulation of dose was linear for both scan lengths. However, for the 271 mm scan the dose was systematically underestimated by the reported CTDI$_{vol}$ (Table IV).

| Table III. Measured values for body CTp selected protocols. $D_{CTp}^{TM}$ refers to the dose estimates investigated in this work. Percent differences are referenced to the measured $D_{CTp}^M$. All values are presented in mGy/100 mAs. |
|---|---|---|---|---|---|---|
| Body CTp | Tube potential | 70 kVp | 80 kVp | 100 kVp | 120 kVp | 140 kVp |
|---|---|---|---|---|---|---|
| 144 mm | $D_{CTp}^M$ | 1.38 | 2.27 | 5.09 | 8.61 | 12.94 |
| CTDI$_{vol}$ (Siemens) | 1.46 | 2.41 | 5.05 | 8.55 | 12.85 |
| Difference (%) | 5.8 | 6.2 | –0.79 | –0.7 | –0.7 |
| $D_{CTp}^{TM}$ (Pave) | 2.11 | 3.73 | 8.31 | 14.07 | 21.02 |
| Difference (%) | 52.9 | 64.3 | 63.3 | 63.4 | 62.4 |
| $D_{CTp}^{TM}$ ($E_{tot}$) | 1.61 | 2.83 | 6.3 | 10.7 | 15.9 |
| Difference (%) | 16.4 | 24.5 | 23.4 | 23.8 | 23.1 |
| 271 mm | $D_{CTp}^M$ | 1.34 | 2.35 | 5.09 | 8.34 | 13.03 |
| CTDI$_{vol}$ (Siemens) | 1.32 | 2.17 | 4.56 | 7.72 | 11.6 |
| Difference (%) | –1.51 | –8.3 | –11.62 | –8.03 | –12.33 |
| $D_{CTp}^{TM}$ (Pave) | 1.45 | 2.6 | 5.69 | 9.63 | 14.4 |
| Difference (%) | 8.3 | 8.4 | 11.7 | 15.4 | 10.4 |
For the 144 mm scans the measurement based doses were similar to the displayed CTDI$_{vol}$ for potentials between 100 and 140 kV, while the doses at lower voltage potentials were systematically overestimated by the reported CTDI$_{vol}$ by 6%. In order to estimate the planar average dose during the body CTp scan employing the shuttle mode from the reference data obtained using uniform pitch helical scans, an average motion of the table was calculated over ten scans, and the variation of pitch with time was determined. The resulting $D_{CTp}^{M}(p_{ave})$ estimate was calculated as per TG111 formalism, scaling the reference $D_{eq,ref}$ by the ratio between the reference scan pitch ($p_{ref} = 0.5$) and calculated average pitch during the body CTp scan ($p_{ave} = 0.59$). The resulting values for this estimate were systematically larger than the displayed CTDI$_{vol}$. The table motion curve was not recorded for the 271 mm scans. The reported CTDI$_{vol}$ systematically underestimated the measured imaging dose $D_{CTp}^{M}$ for this protocol. The $D_{CTp}^{M}(E_{tot})$ estimate overestimated $D_{CTp}^{M}$ for both body CTp protocols, but was more accurate in the case of the longer scan.

### 4. DISCUSSION AND CONCLUSION

The goal of this study was to evaluate imaging dose during variable pitch body CTp protocols. Due to stated limitations of current dosimetric protocols when estimating imaging dose for large collimations and extended scan ranges,$^{3,4}$ TG111 formalism was utilized in this study to measure the equilibrium dose. The TG111 methodology was implemented with ease, and the findings are similar to other studies.$^4$ The reference measurements (uniform pitch) results indicate that the planar average $D_{eq}$ increases with tube potential. The scatter contribution to the central measurement becomes increasingly significant as the tube potential and the length of the scan increase. For a “finite” scan length of 11.2 cm, the planar average $D_{11.2cm}$ is very similar to the CTDI$_{vol}$ values calculated based on 10 cm pencil chamber measurements. As demonstrated before, the increasing difference between CTDI$_{vol}$ values and full scan or “infinite” planar average dose is representative of the underestimation by CTDI metrics of the scatter tails beyond the active length of the pencil chamber.$^{3,4}$ This observation is reflected in the measured imaging dose during body CTp scans. For the shorter 144 cm scan, the CTDI$_{vol}$ is accurate in representing the measured dose for higher energies, more so than for the longer 271 cm scan, where the dose is systematically underestimated by the same metric. For both scan lengths, the dose was linear with the amount of number of scans, indicating that the single scan measurement is an accurate predictor of the imaging dose during multiple scans.

Two adaptations of the TG111 formalism were presented in this study, in an attempt to utilize the TG111 reference data obtained for uniform pitch helical scans, to obtain dose estimates for a variable pitch scan. Both estimates are expected to be conservative as the reference average planar equilibrium dose captures the scattered radiation for an “infinite scan,” taking into account energy deposited outside the geometric limits of the considered body CTp scans. This was the case for the $D_{CTp}^{TG}(E_{tot})$ estimate which was systematically high (>50%) for the 144 mm scan. The explanation for this large discrepancy from $D_{CTp}^{M}$ and difference from $D_{CTp}^{TG}(E_{tot})$ stands in the omission of the overscan regions which was not considered during the calculation of the average pitch directly from the recorded table motion. While still overestimating the planar average dose by more than 15%–20% on average for the 144 mm scan and approximately 10% on average for the 271 mm scan the $D_{CTp}^{TG}(E_{tot})$ estimate was closer to the measurement-based $D_{CTp}^{M}$. Since the longer scan is relatively closer to the equilibrium length, the $D_{CTp}^{TG}(E_{tot})$ estimate was more accurate for the latter protocol.

The $p_{ave}$ method is a highly simplified implementation of the TG111-defined equilibrium dose-pitch product. Scaling $D_{eq,ref}$ with the ratio of the reference pitch (0.5) and the calculated average to obtain a value for the $D_{CTp}^{TG}$ is generally expected to misrepresent the measured value ($D_{CTp}^{M}$). This is because the inverse of the time variable pitch (not the pitch itself) needs to be averaged. This leads to singularities as the Adaptive 4D perfusion scan includes zero pitch regions with no table motion at its extremes. For this reason, the $D_{CTp}^{TG}(E_{tot})$ approximation was also considered. This latter method is also more consistent with the one used for the calculation of the scanner reported CTDI$_{eq}$ values.

Another observation from the measurements used to obtain $D_{eq,ref}$ was that the central dose measurement for the longer scans may have not reached equilibrium (Fig. 2), specifically for higher tube potentials. The difference in measured dose was less than 2% between the last scan and the one before last for all tube potentials. If a longer scan and implicitly a longer phantom were to be used, the increased accuracy in $D_{eq}$ determination would be negligible,$^7$ at the expense of decreased practicality of the setup.

Due to the complex motion of the table, the large collimation, and scan length, it is recommendable that a departure from CTDI-based metrics should be considered in favor of the more direct $D_{eq}$ formalism. The $D_{CTp}^{TG}$ estimate of planar average $D_{eq}$ within the TG111 framework is confounded by two factors: variable pitch during acquisition and scan finite range. Since this would inherently set TG111-based dose estimates high for any scan lengths below the equilibrium length, no simple way of propagating the uniform pitch reference TG111 measurements to the variable pitch scans is obvious. Therefore, we recommend that the $D_{CTp}$ be always directly measured for body CTp protocols.

In conclusion, we have successfully implemented the TG111 formalism to measure the imaging dose during body
perfusion CT studies utilizing variable pitch acquisition. The observations made herein indicate that the TG111 defined equilibrium dose pitch product cannot be implemented with ease in order to propagate uniform pitch reference data to nonuniform pitch scans. Furthermore, direct imaging dose measurement using TG111 should be always the gold standard for these complex acquisition protocols. With the popularity of perfusion imaging increasing in radiation oncology clinics, there is a need for standardization of body CTp protocols, dose reporting, and further acquisition of reference dosimetric data for safe and efficient clinical implementation.

ACKNOWLEDGMENTS

The authors thank the editors and reviewers for constructive criticism and suggestions on the manuscript. The authors report no conflicts of interest in conducting the research.

1Author to whom correspondence should be addressed. Electronic mail: maxente@stanford.edu; Telephone: (650) 723-1530.
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