# Radiation Dose Reduction Strategy for CT Protocols: Successful Implementation in Neuroradiology Section[1]

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**Purpose:** To retrospectively quantify the effect of systematic use of tube current modulation for neuroradiology computed tomographic (CT) protocols on patient dose and image quality.

**Materials and Methods:** This HIPAA-compliant study had institutional review board approval, with waiver of informed consent. The authors evaluated the effect of dose modulation on four types of neuroradiologic CT studies: brain CT performed without contrast material (unenhanced CT) in adult patients, unenhanced brain CT in pediatric patients, adult cervical spine CT, and adult cervical and intracranial CT angiography. For each type of CT study, three series of 100 consecutive studies were reviewed: 100 studies performed without dose modulation, 100 studies performed with z-axis dose modulation, and 100 studies performed with x-y-z–axis dose modulation. For each examination, the weighted volume CT dose index ($CTDI_{vol}$) and dose-length product (DLP) were recorded and noise was measured. Each study was also reviewed for image quality. Continuous variables ($CTDI_{vol}$, DLP, noise) were compared by using *t* tests, and categorical variables (image quality) were compared by using Wilcoxon rank-sum tests.

**Results:** For unenhanced CT of adult brains, the $CTDI_{vol}$ and DLP, respectively, were reduced by 60.9% and 60.3%, respectively, by using z-axis dose modulation and by 50.4% and 22.4% by using x-y-z–axis dose modulation. Significant dose reductions ($P < .001$) were also observed for pediatric unenhanced brain CT, cervical spine CT, and adult cervical and intracranial CT angiography performed with each dose modulation technique. Image quality and noise were unaffected by the use of either dose modulation technique ($P > .05$).

**Conclusion:** Use of dose-modulation techniques for neuroradiology CT examinations affords significant dose reduction while image quality is maintained.



Supplemental material: *http://radiology.rsnajnls.org/cgi/content/full/2472071054/DC1*
*http://radiology.rsnajnls.org/cgi/content/full/2472071054/DC2*

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Studies in both the United States and Europe have revealed that computed tomographic (CT) examinations account for only up to 15% of all imaging examinations but contribute up to 75% of the total radiation dose to the population (1–6). For this reason, radiation dose related to CT scans has become a public health concern. It is important for the radiologist to ensure that CT examinations are indicated and that every possible effort is made to reduce the radiation dose.

CT manufacturers have developed tools to assist radiologists in the endeavor to reduce patient dose. Dose modulation, in which tube current is adjusted separately for each CT section according to patient attenuation, is one of the available tools that permit dose reduction. To date, the effect of implementing dose modulation has been evaluated only for individual CT imaging protocols (7–10), but the overall effect of its systematic use within a radiology department or section is mostly unknown. Thus, our goal was to retrospectively quantify the effect of systematic use of tube current modulation for neuroradiology CT protocols on patient dose and image quality.

## Materials and Methods

### Study Design and Imaging Protocols

The institutional review board of the University of California San Francisco approved this retrospective study, which was in compliance with the Health Insurance Portability and Accountability Act. Informed consent was waived by the institutional review board.

At our institution (the University of California San Francisco), z-axis dose modulation was introduced with our 16-section CT scanner (Lightspeed; GE Healthcare, Milwaukee, Wis) in September 2004. Prior to the introduction of dose modulation, the tube current in milliamperes was decided subjectively by a registered radiology technologist, in a range set by the radiologists, on the basis of different factors, including the patient's body habitus. When z-axis dose modulation was introduced, the same tube current range was maintained, but a computer algorithm altered the tube current applied to each CT section on the basis of a preset noise index (NI). The NI is a parameter indicative of a level of image noise considered to be acceptable to the radiologist for a given CT examination. A lower NI translates into lower noise and thus into an improved signal-to-noise ratio. However, a lower NI requires higher tube current for a given pitch and tube rotation time and therefore delivers higher patient radiation dose. Establishment of acceptable values for the NI in our institution was accomplished over a 3-month period (from September 2004 through November 2004). The NI was initially set at the lowest value (1) and was progressively increased until the image quality was determined to be insufficient. This was a consensus decision by the nine faculty members (who had 6–25 years of experience as of 2004) of our neuroradiology section for the four CT protocols described below (Tables 1–4).

In August 2006, x-y-z–axis dose modulation was introduced with the installation of our 64-section CT scanners (Lightspeed VCT; GE Healthcare). This kind of dose modulation adds one degree of complexity, in the sense that tube current not only varies from section to section but also can be modulated within a section depending on the attenuation along the x-ray beam path. The same adjustment process for the NI was employed over a 6-week period (from August 2006 through September 2006).

We evaluated our four most frequent types of neuroradiologic CT studies: adult brain CT performed without contrast material (unenhanced CT), pediatric unenhanced brain CT, cervical spine CT in adult patients, and CT angiography of the cervical and intracranial vessels in adult patients. For each type of CT study, we included three series of 100 consecutive patients each: The first series underwent CT with a 16-section CT scanner (Lightspeed; GE Healthcare) before the introduction of z-axis dose modulation, the second series underwent CT with a 16-section CT scanner after the introduction of z-axis dose modulation, and the third series underwent CT with a 64-section CT scanner after the introduction of x-y-z–axis dose modulation. Patient demographic data were recorded. The CT studies performed during the two periods of NI adjustment—September 2004 through November 2004 (3 months of practice before enrollment of patients in the second group—the group who underwent CT with z-axis dose modulation) and August 2006 through September 2006 (6 weeks of practice before enrollment of patients in the third group—the group who underwent CT

## Advances in Knowledge

- Utilization of dose-modulation techniques resulted in a significant reduction (up to 60.9%, $P < .001$) in radiation dose to patients for CT studies typically utilized in our neuroradiology section.
- The dose-modulation technique can be implemented without a loss of image quality.

## Implication for Patient Care

- Dose-modulation techniques can be systematically used for neuroradiology CT examinations to reduce patient radiation dose.

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**Abbreviations:**
$CTDI_{vol}$ = volume CT dose index
DLP = dose-length product
NI = noise index

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with x-y-z–axis dose modulation)—were not included in the present study. Practice before enrollment of patients in the first series (the group who underwent CT with no dose modulation) was 12 months. The in-plane resolution (field of view and matrix) for each type of CT study was kept the same for the three series of patients.

For pediatric unenhanced brain CT (Table 2), we developed two categories of indications: "low-dose" indications (hydrocephalus, shunt placement) and "high-dose" indications (nonaccidental trauma, acute neurologic defect, seizure, encephalopathy, and congenital anomalies). Before implementation of dose modulation, technologists were instructed to select low tube current in the 100–150 mA range for low-dose indications and high tube current in the 200–250 mA range for high-dose indications, when image detail was crucial. After implementation of dose modulation, two NI levels were selected for the two types of indications (Table 2).

### Image Analysis

For each patient group and study type, quantitative image noise and subjective image quality were evaluated. Quantitative noise was determined by using a previously reported method (11): measuring the standard deviation of the pixel values in a 100-mm$^2$ region of interest that was drawn by a neuroradiologist (A.B.S., with 6 years of experience) in the background defined as the air surrounding the patient, as far as possible from the patient. For image quality, all studies were reviewed in random order by the same neuroradiologist (A.B.S.). The neuroradiologist was blinded as to whether or not dose modulation had been utilized, to the type of scanner with which the study was performed (16- or 64-section CT scanner), and to the tube current used for the study. The neuroradiologist graded the studies for diagnostic acceptability by using a five-point scale (in which, eg, a score of 1 indicated that the study was unacceptable; a score of 3, that the study was average but diagnostic; and a score of 5, that the study was excellent). Specific criteria were used to judge diagnostic acceptability (Appendix E1, Tables E2–E4; *http://radiology.rsnajnls.org/cgi/content/full/2472071054/DC1*). Grading was based on the ability to define structures and on the sharpness of tissue interfaces. This grading system is similar to those utilized in previous studies by Mulkens et al (9) and Namasivayam et al (10).

**Table 1**

**Imaging Protocols for Unenhanced CT of Brain in Adult Patients**

| Parameter | No Dose Modulation* | z-Axis Dose Modulation | x-y-z–Axis Dose Modulation |
|---|---|---|---|
| Type of scanner | 16-Section | 16-Section | 64-Section |
| Detector configuration† | 4 × 3.75 | 4 × 3.75 | 8 × 2.5 |
| Reconstruction interval (mm) | 3.75 | 3.75 | 2.5 |
| Pitch | Transverse mode | Transverse mode | Transverse mode |
| Rotation time (sec) | 2 | 2 | 1 |
| Peak voltage (kVp) | 120 | 120 | 120 |
| Tube current (mA) | 200–400‡ | Determined with dose modulation | Determined with dose modulation |
| NI | NA | 4 | 4 |
| Minimal tube current (mA) | NA | 50 | 50 |
| Maximal tube current (mA) | NA | 400 | 400 |

* NA = not applicable.
† Number of sections × section thickness in millimeters.
‡ Chosen by the technologist.

**Table 2**

**Imaging Protocols for Unenhanced CT of Brain in Pediatric Patients**

| Parameter | No Dose Modulation* | z-Axis Dose Modulation | x-y-z–Axis Dose Modulation |
|---|---|---|---|
| Type of scanner | 16-Section | 16-Section | 64-Section |
| Detector configuration | 4 × 3.75 | 4 × 3.75 | 8 × 2.5 |
| Reconstruction interval (mm) | 3.75 | 3.75 | 2.5 |
| Pitch | Transverse mode | Transverse mode | Transverse mode |
| Rotation time (sec) | 1 | 1 | 1 |
| Peak voltage (kVp) | 120 | 120 | 120 |
| Tube current (mA) | 100–150 (Low dose) and 200–250 (high dose)† | Determined with dose modulation | Determined with dose modulation |
| NI | NA | 12 (Low dose) or 4 (high dose) | 12 (Low dose) or 4 (high dose) |
| Minimal tube current (mA) | NA | 50 | 50 |
| Maximal tube current (mA) | NA | 250 | 300 |

* NA = not applicable.
† Chosen by the technologist.

## Radiation Dose

Radiation dose to the patient was monitored for each study by means of the two standard dose indicators—volume CT dose index ($CTDI_{vol}$) and dose-length product (DLP)—that were calculated by the CT scanner for each CT study and were automatically saved to a dose report on our picture archiving and communication system. The $CTDI_{vol}$ parameter is representative of the average dose delivered within the reconstructed section. The $CTDI_{vol}$ represents the weighted CT dose index divided by the pitch and describes the average dose throughout a 160-mm-diameter circular Plexiglas phantom, incorporating the central dose weighted by a 1/3 factor and the peripheral dose weighted by a 2/3 factor. The DLP can be related to energy imparted to organs and can thus be used to assess the overall radiation burden of a given examination. It is equal to the product of the $CTDI_{vol}$ and the length of the scan in centimeters (12).

## Statistical Analysis

For each type of CT study, differences between the three groups of patients in terms of demographic data, radiation dose descriptors, image quality, and noise were evaluated for statistical significance. Unpaired *t* tests were used to compare continuous variables between groups; Wilcoxon rank-sum (Mann-Whitney) tests were used for categorical variables such as image quality scores. The statistical significance level was set at .05. Statistical analysis was performed by using software (Stata, version 9.2; Stata, College Station, Tex).

**Table 3**

**Imaging Protocols for CT of Cervical Spine in Adult Patients**

| Parameter | No Dose Modulation* | z-Axis Dose Modulation | x-y-z–Axis Dose Modulation |
|---|---|---|---|
| Type of scanner | 16-Section | 16-Section | 64-Section |
| Detector configuration | 4 × 1.25 | 4 × 1.25 | 64 × 0.625 |
| Reconstruction interval (mm) | 1 | 1 | 0.5 |
| Pitch | 1.375:1 | 1.375:1 | 0.984:1 |
| Rotation time (sec) | 0.8 | 0.8 | 0.8 |
| Peak voltage (kVp) | 120 | 120 | 120 |
| Tube current (mA) | 200–450† | Determined with dose modulation | Determined with dose modulation |
| NI | NA | 12 | 12 |
| Minimal tube current (mA) | NA | 50 | 50 |
| Maximal tube current (mA) | NA | 450 | 450 |

* NA = not applicable.

† Chosen by the technologist.

**Table 4**

**Imaging Protocols for Cervical and Intracranial CT Angiography in Adult Patients**

| Parameter | No Dose Modulation* | z-Axis Dose Modulation | x-y-z–Axis Dose Modulation |
|---|---|---|---|
| Type of scanner | 16-Section | 16-Section | 64-Section |
| Detector configuration | 4 × 1.25 | 4 × 1.25 | 64 × 0.625 |
| Reconstruction interval (mm) | 1 | 1 | 0.5 |
| Pitch | 1.375:1 | 1.375:1 | 0.984:1 |
| Rotation time (sec) | 0.5 | 0.5 | 0.5 |
| Peak voltage (kVp) | 120 | 120 | 120 |
| Tube current (mA) | 200–450† | Determined with dose modulation | Determined with dose modulation |
| NI | NA | 4 | 6 |
| Minimal tube current (mA) | NA | 50 | 50 |
| Maximal tube current (mA) | NA | 450 | 450 |

## Results

### Study Patients

There were no significant demographic differences among the three groups of patients (those undergoing CT with no dose modulation, z-axis dose modulation, or x-y-z–axis dose modulation) (Table E5, *http://radiology.rsnajnls.org/cgi/content/full/2472071054/DC2*). This was true for the four types of CT studies that were assessed.

### Radiation Dose

With the 16-section scanner, both $CTDI_{vol}$ and DLP were lowered by up to 60.9% for unenhanced brain CT in adults performed by using dose modulation compared with these values for unenhanced brain CT performed without dose modulation (Table 5). With the 64-section scanner, a 3.75-mm section thickness could not be obtained, and thinner 2.5-mm sections were obtained instead, resulting in a greater number of sections for the 64-section scanner. Also, the tube current and $CTDI_{vol}$ were greater for the 64-section scanner when x-y-z–axis dose modulation was used than for the 16-section scanner when z-axis dose modulation was used, so that we could achieve the same NI for a thinner section thickness with the 64-section scanner.

Regarding pediatric unenhanced brain CT (Table 6), $CTDI_{vol}$ and DLP were lowered by up to 57.9% when dose modulation was used compared with $CTDI_{vol}$ and DLP when dose modulation was not used. The same differences in terms of numbers of sections, tube current, $CTDI_{vol}$, and DLP as in the adult patients were observed between the three groups of pediatric patients.

Regarding cervical spine CT in adult patients (Table 7), $CTDI_{vol}$ and DLP were lowered by up to 37.4% when dose modulation was used compared with $CTDI_{vol}$ and DLP when dose modulation was not used.

Regarding cervical and intracranial CT angiography in adult patients (Table 8), $CTDI_{vol}$ and DLP were lowered by up to 38.5% when dose modulation was used compared with $CTDI_{vol}$ and DLP when dose modulation was not used.

## Image Quality and Noise

Image quality and noise were not affected by the use of dose-modulation algorithms (Tables E6–E9, *http://radiology.rsnajnls.org/cgi/content/full/2472071054/DC2*).

## Discussion

The results of our study demonstrate that use of dose modulation as a radiation dose reduction tool for the CT examinations most frequently performed in our neuroradiology section resulted in a substantial reduction in radiation dose while image quality was maintained. Dose modulation requires selection of an acceptable noise level and a range of tube currents, after which a computer algorithm adjusts x-ray tube current to the appropriate amount within this range. This achieves the selected signal-to-noise ratio in the CT sections given the patient's attenuation and girth at each level. Identification of optimal signal-to-noise ratio for each type of CT protocol requires fine tuning to lower the tube current as much as possible while preserving image quality.

The effect of dose modulation on unenhanced brain CT was uncertain at onset given that the head is a spheroid structure with similar attenuation throughout, which differs from other body parts, such as the chest. Nevertheless, we found that dose modulation resulted in significant reductions in radiation dose to adults and children ($P < .001$). Indeed, for adult unenhanced brain CT, $CTDI_{vol}$ and DLP, respectively, were reduced by 60.9% and 60.3% by using z-axis dose modulation

**Table 5**

**Radiation Dose for Unenhanced CT of Brain in Adult Patients**

| Parameter | 16-Section CT with No Dose Modulation* | 16-Section CT with z-Axis Dose Modulation* | 64-Section CT with x-y-z-Axis Dose Modulation* | 16-Section CT with No Dose Modulation vs 16-Section CT with z-Axis Dose Modulation† | 16-Section CT with No Dose Modulation vs 64-Section CT with x-y-z-Axis Dose Modulation† | 16-Section CT with z-Axis Dose Modulation vs 64-Section CT with x-y-z-Axis Dose Modulation† |
|---|---|---|---|---|---|---|
| No. of sections | 40.5 ± 3.8 (32–44) | 41.2 ± 2.5 (32–44) | 63.4 ± 4.2 (48–72) | +1.6 (−0.5, +3.9) [.915] | +56.3 (+53.8, +59.3) [<.001] | +53.8 (+51.6, +56.2) [<.001] |
| Tube current (mA)‡ | 233.1 ± 71.1 (200–400) | 91.1 ± 23.3 (61.9–136.3) | 222.9 ± 78.7 (78.1–292.3) | −60.9 (−67.2, −54.6) [<.001] | −4.4 (−13.3, +4.5) [.282] | +144.7 (+127.0, +162.3) [<.001] |
| $CTDI_{vol}$ (mGy) | 92.7 ± 28.3 (79.5–159.1) | 36.2 ± 6.2 (24.6–54.2) | 46.0 ± 6.6 (16.1–60.3) | −60.9 (−67.1, −58.4) [<.001] | −50.4 (−56.5, −44.2) [<.001] | +27.1 (+22.2, +32.0) [<.001] |
| DLP (mGy · cm) | 1409.4 ± 451.5 (1193.0–2147.3) | 559.5 ± 124.0 (369.3–731.8) | 1093.4 ± 117.5 (387.0–1267.3) | −60.3 (−66.8, −53.8) [<.001] | −22.4 (−28.9, −15.9) [<.001] | +95.4 (+89.4, +101.4) [<.001] |

* Data are means ± standard deviations, with ranges in parentheses.

† Data are relative differences expressed as percentages, with 95% confidence intervals (also expressed as percentages) in parentheses and *P* values in square brackets. Relative difference for comparing A and B protocols was calculated as the absolute value for the B protocol minus the absolute value for the A protocol, with this difference then divided by the absolute value for the A protocol. Absolute values are shown in the first three columns of the table.

‡ Mean tube current for the dose-modulation CT studies.

**Table 6**

**Radiation Dose for Unenhanced CT of Brain in Pediatric Patients**

| Parameter | 16-Section CT with No Dose Modulation* | 16-Section CT with z-Axis Dose Modulation* | 64-Section CT with x-y-z-Axis Dose Modulation* | 16-Section CT with No Dose Modulation vs 16-Section CT with z-Axis Dose Modulation† | 16-Section CT with No Dose Modulation vs 64-Section CT with x-y-z-Axis Dose Modulation† | 16-Section CT with z-Axis Dose Modulation vs 64-Section CT with x-y-z-Axis Dose Modulation† |
|---|---|---|---|---|---|---|
| No. of sections | 37.3 ± 5.7 (24–44) | 39.5 ± 5.0 (24–44) | 58.4 ± 6.5 (32–72) | +6.0 (+1.9, +9.9) [.099] | +56.7 (+52.0, +61.1) [<.001] | +47.8 (+43.8, +51.9) [<.001] |
| Tube current (mA)‡ | 171.4 ± 30.6 (100–250) | 72.1 ± 42.5 (50–192.3) | 156.4 ± 69.1 (50–278.6) | −57.9 (−63.9, −51.9) [<.001] | −8.8 (−17.4, −0.1) [.113] | +116.9 (+94.9, +139.0) [<.001] |
| $CTDI_{vol}$ (mGy) | 68.2 ± 12.2 (39.8–99.4) | 28.7 ± 15.5 (19.9–76.5) | 32.3 ± 11.4 (10.3–57.5) | −57.9 (−63.6, −52.2) [<.001] | −52.6 (−57.4, −47.8) [<.001] | +12.6 (−0.6, +25.7) [.097] |
| DLP (mGy · cm) | 952.7 ± 237.9 (477.2–1491.2) | 424.7 ± 272.7 (238.8–1114.7) | 707.1 ± 200.3 (216.8–1207.9) | −55.4 (−62.9, −48.0) [<.001] | −25.8 (−32.2, −19.4) [<.001] | +66.5 (+50.9, +82.1) [<.001] |

* Data are means ± standard deviations, with ranges in parentheses.

† Data are relative differences expressed as percentages, with 95% confidence intervals (also expressed as percentages) in parentheses and *P* values in square brackets. Relative difference for comparing A and B protocols was calculated as the absolute value for the B protocol minus the absolute value for the A protocol, with this difference then divided by the absolute value for the A protocol. Absolute values are shown in the first three columns of the table.

‡ Mean tube current for the dose-modulation CT studies.

**Table 7**

**Radiation Dose for CT of Cervical Spine in Adult Patients**

| Parameter | 16-Section CT with No Dose Modulation* | 16-Section CT with z-Axis Dose Modulation* | 64-Section CT with x-y-z–Axis Dose Modulation* | 16-Section CT with No Dose Modulation vs 16-Section CT with z-Axis Dose Modulation† | 16-Section CT with No Dose Modulation vs 64-Section CT with x-y-z–Axis Dose Modulation† | 16-Section CT with z-Axis Dose Modulation vs 64-Section CT with x-y-z–Axis Dose Modulation† |
|---|---|---|---|---|---|---|
| No. of sections | 233.2 ± 29.3 (199–398) | 225.0 ± 37.0 (179–390) | 420.0 ± 63.7 (398–777) | −3.2 (−7.5, +0.5) [.405] | +80.2 (+74.2, +86.0) [<.001] | +86.1 (+80.2, +93.1) [<.001] |
| Tube current (mA)‡ | 304.9 ± 95.4 (200–450) | 197.0 ± 76.7 (83–450) | 256.5 ± 102.5 (93.2–450) | −35.3 (−43.3, −27.5) [<.001] | −15.9 (−24.9, −6.9) [<.001] | +30.1 (+17.5, +42.9) [<.001] |
| $CTDI_{vol}$ (mGy) | 18.6 ± 6.1 (12.2–27.4) | 12.0 ± 7.9 (5.1–27.4) | 17.2 ± 7.4 (6.3–30.2) | −35.3 (−46.0, −25.0) [<.001] | −7.3 (−17.6, +2.6) [.125] | +43.3 (+25.7, +47.6) [.009] |
| DLP (mGy · cm) | 433.0 ± 163.9 (366.6–1019.5) | 271.2 ± 124.6 (129.4–855) | 361.5 ± 153.7 (167.6–961.7) | −37.4 (−46.7, −28.0) [<.001] | −16.5 (−26.7, −6.3) [.102] | +33.3 (+19.0, +47.6) [.012] |

* Data are means ± standard deviations, with ranges in parentheses.

† Data are relative differences expressed as percentages, with 95% confidence intervals (also expressed as percentages) in parentheses and *P* values in square brackets. Relative difference for comparing A and B protocols was calculated as the absolute value for the B protocol minus the absolute value for the A protocol, with this difference then divided by the absolute value for the A protocol. Absolute values are shown in the first three columns of the table.

‡ Mean tube current for the dose-modulation CT studies.

**Table 8**

**Radiation Dose for Cervical and Intracranial CT Angiography in Adult Patients**

| Parameter | 16-Section CT with No Dose Modulation* | 16-Section CT with z-Axis Dose Modulation* | 64-Section CT with x-y-z–Axis Dose Modulation* | 16-Section CT with No Dose Modulation vs 16-Section CT with z-Axis Dose Modulation† | 16-Section CT with No Dose Modulation vs 64-Section CT with x-y-z–Axis Dose Modulation† | 16-Section CT with z-Axis Dose Modulation vs 64-Section CT with x-y-z–Axis Dose Modulation† |
|---|---|---|---|---|---|---|
| No. of sections | 360.6 ± 35.0 (266–470) | 366.5 ± 28.7 (287–431) | 746.4 ± 70.1 (563–955) | +1.7 (−0.8, +4.1) [.344] | +107 (+102.7, +111.2) [<.001] | +103.6 (+99.6, +107.7) [<.001] |
| Tube current (mA) | 328.2 ± 58.9 (200–450) | 201.7 ± 28.2 (149.1–261.7) | 307.5 ± 46.9 (164.7–329.8) | −38.5 (−42.4, −33.4) [<.001] | −6.3 (−10.8, −1.8) [.078] | +52.5 (+47.1, +57.7) [<.001] |
| $CTDI_{vol}$ (mGy) | 11.0 ± 2.0 (6.7–15.2) | 6.8 ± 1.8 (5.5–8.8) | 10.3 ± 1.2 (5–11) | −38.5 (−43.0, −33.4) [<.001] | −6.6 (−10.5, −2.2) [.086] | +52 (+45.2, +57.7) [<.001] |
| DLP (mGy · cm) | 398.4 ± 104.9 (218.8–604.5) | 248.9 ± 34.1 (202.4–341) | 385.0 ± 53.6 (194.2–454.4) | −37.5 (−43.0, −32.1) [<.001] | −3.3 (−9.2, +2.4) [.457] | +54.8 (+49.7, +59.7) [<.001] |

* Data are means ± standard deviations, with ranges in parentheses.

† Data are relative differences expressed as percentages, with 95% confidence intervals (also expressed as percentages) in parentheses and *P* values in square brackets. Relative difference for comparing A and B protocols was calculated as the absolute value for the B protocol minus the absolute value for the A protocol, with this difference then divided by the absolute value for the A protocol. Absolute values are shown in the first three columns of the table.

‡ Mean tube current for the dose-modulation CT studies.

and by 50.4% and 22.4% by using x-y-z–axis dose modulation. Of note, z-axis dose modulation was used with a 16-section CT scanner, with which the section thickness classically used was 3.75 mm. When we transitioned to a 64-section CT scanner, x-y-z–axis dose modulation was used. With the latter scanner, the 3.75-mm section thickness was no longer available. We initially tried 5 mm, but this section thickness was judged to be insufficient by our faculty in terms of spatial resolution, and we selected 2.5 mm instead. This required an increase in tube current compared with that used with the 16-section CT scanner to maintain the same noise level. Because gantry rotation was 2 seconds for the 16-section CT scanner and 1 second for the 64-section CT scanner, 182.2 mAs (91.1 mA · 2 seconds) and 222.9 mAs (222.9 mA · 1 second) were used with these two types of CT scanners, respectively. Compared with the 16-section CT scanner with z-axis modulation, the 64-section CT scanner with x-y-z–axis modulation yielded lower $CTDI_{vol}$ and especially lower DLP reduction but provided images with better longitudinal resolution (thinner detector configuration and section thickness).

Lower DLP reduction was contributed to by a slightly larger spatial coverage along the z-axis. It may also have been contributed to by factors such as beam filtration and the distance of the focal spot from the system isocenter, as well as by an overranging phenomenon (also called z-overscanning) (13). Overranging happens in helical scan mode because the reconstruction algorithm requires extra rotations on both sides, outside the planned length for data interpolation during image reconstruction (14). This results in radiation exposure of tissues beyond the boundaries of the volume to be imaged (15). In our case, when the detector configuration went from 4 × 3.75 mm (beam collimation of 15 mm with the 16-section scanner) to 8 × 2.5 mm (beam collimation of 20 mm with the 64-section scanner), the $CTDI_{vol}$ increased from 36.2 mGy to 46.0 mGy (approximately 30%), and, for the same scanned length, the DLP should have increased in the same proportion. However, our results show that the DLP increased by 95% (from 560 to 1093 mGy · cm). The increment (95% rather than 30%) is due to the overranging phenomenon, which would have been even worse had a beam collimation of 40 mm been used with the 64-section scanner. Overranging is a major issue when scanning a small length (such as the brain) or when trying to spare some organs (lenses, thyroid gland) from radiation during a CT study (15,16). CT manufacturers are presently trying to address this issue, which will be of even greater concern for increasing detector-width CT scanners such as the 256-section CT scanner.

Radiation doses associated with pediatric unenhanced brain CT were lower than in adults. This was due to the smaller size of the head in pediatric patients and increased awareness about radiation risk in children at baseline, which resulted in lower tube current being used before implementation of dose modulation. Two protocols, high dose and low dose, were already being utilized, depending on the clinical indication for the study. However, dose modulation afforded additional dose reduction for both types of indications ($CTDI_{vol}$ and DLP, respectively, were reduced by 57.9% and 55.4% with z-axis dose modulation and by 52.6% and 25.8% with x-y-z–axis dose modulation).

Cervical spine CT and CT angiography were different from unenhanced brain CT in that the attenuation changed more markedly through the scan in cervical spine CT and CT angiography because of variations in anatomy, which is appropriate for the dose-modulation approach. However, a thinner section thickness (1.25 or 0.625 mm) is required to achieve better spatial resolution and enable assessment of fine anatomic details in these studies. Overall, the use of thinner sections resulted in a dose reduction that was significant ($P < .001$) but less pronounced than that at unenhanced brain CT. CT angiographic studies, in addition, require better contrast resolution, which is reflected by the selection of lower NIs (4–6 for CT angiography, 12 for cervical spine CT) corresponding to increased signal-to-noise ratios.

For all types of studies, dose reduction was less with the 64-section CT scanner than with the 16-section CT scanner, despite the use of x-y-z–axis dose modulation (z-axis dose modulation was used with the 16-section CT scanner). This is likely explained by a trend of obtaining more and thinner sections with the 64-section CT scanner and to the overranging phenomenon mentioned above and thus is probably unrelated to the dose-modulation approach. Dose modulation, however, was instrumental in maintaining acceptable radiation doses for 64-section CT scanner protocols despite the increase in the number of sections and the decrease in section thickness.

There were limitations to our study. Because our study was performed with CT scanners from one manufacturer only, these results should be confirmed in studies that evaluate CT scanners from other vendors. However, we do not anticipate substantial differences, as the principle and effect of tube current modulation should be similar among instruments from different vendors. Also, we did not investigate the effect of dose modulation on all our CT protocols, but rather limited our evaluation to the types of CT studies most frequently performed in our department. Our comparisons focused on the switch from 16-section to 64-section CT scanners but may have been confounded by other changes in practice that occurred over time, such as changes in radiology technology staff. Finally, we included 64-section CT scanner protocols with x-y-z–axis dose modulation in our comparison, even if they differed substantially from 16-section CT protocols (the effect of this difference is detailed in Appendix E1, *http://radiology.rsnajnls.org/cgi/content/full/2472071054/DC1*) and even though we did not perform any study with the 64-section CT scanner without dose modulation. After introducing dose modulation with our 16-section CT scanners and observing the significant associated dose reduction, it would have been unethical, in our opinion, not to implement dose modulation with the 64-section CT scanners when they were installed. We could have limited our report to 16-section CT scanners, but we believed that it was important to report dose findings for the 64-section CT scanner as well, considering the growing number of such scanners being installed worldwide.

In conclusion, we recommend routine use of dose modulation for neuroradiology CT examinations, because this approach affords a significant dose reduction while preserving image quality. Implementation of dose modulation requires a fine-tuning process to identify optimal signal-to-noise level for each type of CT study performed.

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