Automatic Tube Current Modulation and Tube Voltage Selection in Pediatric Computed Tomography

A Phantom Study on Radiation Dose and Image Quality

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Objectives: The aim of this study was to investigate the effects of a modern automatic tube current modulation (ATCM) and automatic tube voltage selection (ATVS) system on radiation dose and image quality in pediatric head, and torso computed tomography (CT) examinations for various clinical indications.

Materials and Methods: Four physical anthropomorphic phantoms that represent the average individual as neonate, 1-year-old, 5-year-old, and 10-year-old child were used. Standard head, thorax, and abdomen/pelvis acquisitions were performed with (1) fixed tube current, (2) ATCM, and (3) ATVS. Acquisitions were performed at various radiation dose levels to generate images at different levels of quality. Reference volume CT dose index (CTDIvol), reference image noise, and reference contrast-to-noise ratios were determined. The potential dose reductions with ATCM and ATVS were assessed.

Results: The percent reduction of CTDIvol with ATCM ranged from 8% to 24% for head, 16% to 39% for thorax, and 25% to 41% for abdomen/pelvis. The percent reduction of CTDIvol with ATVS varied on the clinical indication. In CT angiography, ATVS resulted to the highest dose reduction, which was up to 70% for head, 77% for thorax, and 34% for abdomen/pelvis. In noncontrast examinations, ATVS increased dose by up to 21% for head, whereas reduced dose by up to 34% for thorax and 48% for abdomen/pelvis.

Conclusions: In pediatric CT, the use of ATCM significantly reduces radiation dose and maintains image noise. The additional use of ATVS further reduces the radiation dose for thorax and abdomen/pelvis, and maintains contrast-to-noise ratio for the specified clinical diagnostic task.

Key Words: optimization in CT, pediatric head and body CT, automatic tube current modulation, automatic tube voltage selection, image quality

Received for publication September 14, 2018; and accepted for publication, after revision, October 26, 2018.

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Conflicts of interest and sources of funding: This project has received funding from the Euratom research and training program 2014–2018 under grant agreement No. 755523 (MEDIRAD). The funding source had no role in study design, in the collection, analysis, and interpretation of data, nor in the writing or submission of the report. Supplemental digital contents are available for this article. Direct URL citations appear in the printed text and are provided in the HTML and PDF versions of this article on the journal’s Web site (www.investigativeradiology.com).

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ISSN: 0020-9969/19/5405–0265
DOI: 10.1097/RLI.0000000000000537

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an mA modulation-related parameter, which allows the operator to determine the amount of noise that will be present in the reconstructed images. The clinical mode allows the operator to define the required image contrast on the anatomy of interest, based on the diagnostic task of the examination. Four different clinical mode options are available, which correspond to different levels of image contrast and different levels dose compared with REP (Table 1).

**CT Examination Protocols**

Head, thorax, and abdomen/pelvis acquisitions were performed (Fig. 2). Phantoms were accurately aligned with the gantry isocenter, while in the supine position. Each phantom was scanned using protocols A, B, and C. In protocol A, the scanning parameters recommended by the REPs for pediatric patients were used (Table 2). By default, these protocols are performed with ATCM and ATVS deactivated. Moreover, by default, these protocols are designed to generate images using the standard filtered back projection (FBP) algorithm. To exploit the potential of iterative reconstruction in generating images at a lower noise compared with FBP, the adaptive statistical iterative reconstruction (ASIR) algorithm was activated in all examination protocols. The scanner reported CTDIvol value at each REP was then downscaled using the “inverse square route of image noise” relationship ($CTDI_{vol} \propto 1/\sqrt{\text{imagenoise}}$), so that images generated with ASIR and FBP were at the same noise level.

In protocol B, ATCM was activated. To investigate the effect of ATCM on radiation dose and image noise, consecutive acquisitions were performed with the NI ranging from 3 to 8 for head and 9 to 15 for thorax and abdomen/pelvis. In protocol C, ATVS was additionally activated. To investigate the effect of clinical mode on radiation dose and image contrast, acquisitions were performed at all clinical modes. Besides, at each clinical mode, consecutive acquisitions were performed with the NI ranging from 3 to 8 for head and 9 to 15 for thorax and abdomen/pelvis.

Three cylindrical plastic vials (diameter, 10 mm; volume, 5 mL) containing iodine contrast (Iopamiro 370; Bracco Imaging, Italy) diluted with pure water at 2.5, 5, and 10 mg I/mL were prepared. These vials along with one vial containing pure water were accommodated at the posterior surface of each phantom at the level of the eyes for head, heart for thorax, and middle abdomen for abdomen/pelvis (Fig. 3).

**TABLE 1. The Four Clinical Mode Options**

| Clinical Mode     | Scan Situation                  | Region of Primary Importance     |
|-------------------|---------------------------------|----------------------------------|
| CTA: CT Angiography | Iodinated contrast agent is used | Enhanced tissue regions          |
| BONE: Bone, noncontrast | Contrast agents are not used | Bone regions                      |
| C+: Soft tissue, contrast-enhanced | Iodinated contrast agent is used | Both enhanced and unenhanced tissue regions |
| C−: Soft tissue, noncontrast | Contrast agents are not used | Unenhanced tissue regions        |

“CTA” for CT angiography examinations, “BONE” for examinations that bones are the anatomy of primary diagnostic interest, “C+” for contrast-enhanced examinations that both contrast-enhanced and unenhanced soft tissue anatomies are of diagnostic importance, and “C−” for examinations performed without contrast agents.

CT indicates computed tomography.
Quantitative Image Quality Assessment

Circular regions of interest (ROIs) were manually drawn on uniform brain-equivalent areas for head, and soft tissue-equivalent areas for torso. Regions of interest were also drawn on bone-equivalent areas (Fig. 3). Regions of interest were drawn at the axial level superior to eyes for head, the middle heart level for thorax, and the middle abdomen level for abdomen/pelvis. The mean Hounsfield unit (HU) value obtained from each ROI was recorded. Image noise was measured as the standard deviation (SD) of the mean HU. Mean HU and SD were recorded from acquisitions performed with protocols A, B at all NIs, and C at all clinical modes and NIs. To reduce measurement error, each parameter was measured 3 times on 3 consecutive image slices.

The CNR of iodine (CNR) was calculated as: \[ \text{CNR}_{\text{I}} = \frac{(\text{HU}_{\text{I}} - \text{HU}_{\text{ST}})}{\text{SD}_{\text{ST}}} \], where \( \text{HU}_{\text{I}} \) is the mean HU in 3 iodinated vials, \( \text{HU}_{\text{ST}} \) is the mean HU in brain or soft tissue equivalent areas, and \( \text{SD}_{\text{ST}} \) is corresponding image noise. The CNR of bone (CNR) was calculated as: \[ \text{CNR}_{\text{B}} = \frac{(\text{HU}_{\text{B}} - \text{HU}_{\text{ST}})}{\text{SD}_{\text{ST}}} \], where \( \text{HU}_{\text{B}} \) is the mean HU in bone equivalent areas. The CNR of soft tissue (CNR) was calculated as: \[ \text{CNR}_{\text{ST}} = \frac{(\text{HU}_{\text{ST}} - \text{HU}_{\text{W}})}{\text{SD}_{\text{W}}} \], where \( \text{HU}_{\text{W}} \) is the mean HU in the pure water vial, and \( \text{SD}_{\text{W}} \) is the corresponding image noise. Quantitative image analysis was performed using the ImageJ image analysis software (1.52d; National Institutes of Health, Maryland).

Protocol B: The Effect of ATCM on Reference NI, Reference CNR, and Reference Radiation Dose

To investigate the effect of user-defined NI on image noise, NI versus image noise linear fits were generated. The fitting parameters were used to estimate the NI that generates images at a noise equal to images obtained with protocol A. This NI is designated hereafter as ATCM-reference NI (NIATCM). CNR, CNR, and CNR were calculated at all NIs. Polynomial fits of CNR, CNR, and CNR versus NI were generated. The fitting parameters were used to estimate the CNR, CNR, and CNR values for the \( \text{NI}_{\text{ATCM}} \) determined previously. These values are designated hereafter as \( \text{CNR}_{\text{ATCM}} \), \( \text{CNR}_{\text{ATCM}} \), and \( \text{CNR}_{\text{ATCM}} \), respectively.

To calculate the percent radiation dose difference between protocols A and B (%\( \text{D}_{\text{AB}} \)), the following equation was applied:

\[
\% \text{D}_{\text{AB}} = \frac{\text{CTDIvol}_A - \text{CTDIvol}_B}{\text{CTDIvol}_A} \times 100\% \quad (1)
\]

where \( \text{CTDIvol}_A \) is the CTDIvol value prescribed by protocol A, and \( \text{CTDIvol}_B \) is the CTDIvol prescribed by protocol B at \( \text{NI}_{\text{ATCM}} \).

Quantitative Image Analysis

Circular regions of interest (ROIs) were manually drawn on uniform brain-equivalent areas for head, and soft tissue-equivalent areas for torso. Regions of interest were also drawn on bone-equivalent areas (Fig. 3). Regions of interest were drawn at the axial level superior to eyes for head, the middle heart level for thorax, and the middle abdomen level for abdomen/pelvis. The mean Hounsfield unit (HU) value obtained from each ROI was recorded. Image noise was measured as the standard deviation (SD) of the mean HU. Mean HU and SD were recorded from acquisitions performed with protocols A, B at all NIs, and C at all clinical modes and NIs. To reduce measurement error, each parameter was measured 3 times on 3 consecutive image slices.

The CNR of iodine (CNR) was calculated as: \[ \text{CNR}_{\text{I}} = \frac{(\text{HU}_{\text{I}} - \text{HU}_{\text{ST}})}{\text{SD}_{\text{ST}}} \], where \( \text{HU}_{\text{I}} \) is the mean HU in 3 iodinated vials, \( \text{HU}_{\text{ST}} \) is the mean HU in brain or soft tissue equivalent areas, and \( \text{SD}_{\text{ST}} \) is corresponding image noise. The CNR of bone (CNR) was calculated as: \[ \text{CNR}_{\text{B}} = \frac{(\text{HU}_{\text{B}} - \text{HU}_{\text{ST}})}{\text{SD}_{\text{ST}}} \], where \( \text{HU}_{\text{B}} \) is the mean HU in bone equivalent areas. The CNR of soft tissue (CNR) was calculated as: \[ \text{CNR}_{\text{ST}} = \frac{(\text{HU}_{\text{ST}} - \text{HU}_{\text{W}})}{\text{SD}_{\text{W}}} \], where \( \text{HU}_{\text{W}} \) is the mean HU in the pure water vial, and \( \text{SD}_{\text{W}} \) is the corresponding image noise. Quantitative image analysis was performed using the ImageJ image analysis software (1.52d; National Institutes of Health, Maryland).

Protocol B: The Effect of ATCM on Reference NI, Reference CNR, and Reference Radiation Dose

To investigate the effect of user-defined NI on image noise, NI versus image noise linear fits were generated. The fitting parameters were used to estimate the NI that generates images at a noise equal to images obtained with protocol A. This NI is designated hereafter as ATCM-reference NI (NIATCM).

CNR, CNR, and CNR were calculated at all NIs. Polynomial fits of CNR, CNR, and CNR versus NI were generated. The fitting parameters were used to estimate the CNR, CNR, and CNR values for the \( \text{NI}_{\text{ATCM}} \) determined previously. These values are designated hereafter as \( \text{CNR}_{\text{ATCM}} \), \( \text{CNR}_{\text{ATCM}} \), and \( \text{CNR}_{\text{ATCM}} \), respectively.

To calculate the percent radiation dose difference between protocols A and B (%\( \text{D}_{\text{AB}} \)), the following equation was applied:

\[
\% \text{D}_{\text{AB}} = \frac{\text{CTDIvol}_A \text{CTDIvol}_B}{\text{CTDIvol}_A} \times 100\% \quad (1)
\]

where \( \text{CTDIvol}_A \) is the CTDIvol value prescribed by protocol A, and \( \text{CTDIvol}_B \) is the CTDIvol prescribed by protocol B at \( \text{NI}_{\text{ATCM}} \).

Quantitative Image Analysis

Circular regions of interest (ROIs) were manually drawn on uniform brain-equivalent areas for head, and soft tissue-equivalent areas for torso. Regions of interest were also drawn on bone-equivalent areas (Fig. 3). Regions of interest were drawn at the axial level superior to eyes for head, the middle heart level for thorax, and the middle abdomen level for abdomen/pelvis. The mean Hounsfield unit (HU) value obtained from each ROI was recorded. Image noise was measured as the standard deviation (SD) of the mean HU. Mean HU and SD were recorded from acquisitions performed with protocols A, B at all NIs, and C at all clinical modes and NIs. To reduce measurement error, each parameter was measured 3 times on 3 consecutive image slices.

The CNR of iodine (CNR) was calculated as: \[ \text{CNR}_{\text{I}} = \frac{(\text{HU}_{\text{I}} - \text{HU}_{\text{ST}})}{\text{SD}_{\text{ST}}} \], where \( \text{HU}_{\text{I}} \) is the mean HU measured in 3 iodinated vials, \( \text{HU}_{\text{ST}} \) is the mean HU in brain or soft tissue equivalent areas, and \( \text{SD}_{\text{ST}} \) is corresponding image noise. The CNR of bone (CNR) was calculated as: \[ \text{CNR}_{\text{B}} = \frac{(\text{HU}_{\text{B}} - \text{HU}_{\text{ST}})}{\text{SD}_{\text{ST}}} \], where \( \text{HU}_{\text{B}} \) is the mean HU in bone equivalent areas. The CNR of soft tissue (CNR) was calculated as: \[ \text{CNR}_{\text{ST}} = \frac{(\text{HU}_{\text{ST}} - \text{HU}_{\text{W}})}{\text{SD}_{\text{W}}} \], where \( \text{HU}_{\text{W}} \) is the mean HU in the pure water vial, and \( \text{SD}_{\text{W}} \) is the corresponding image noise. Quantitative image analysis was performed using the ImageJ image analysis software (1.52d; National Institutes of Health, Maryland).

Protocol B: The Effect of ATCM on Reference NI, Reference CNR, and Reference Radiation Dose

To investigate the effect of user-defined NI on image noise, NI versus image noise linear fits were generated. The fitting parameters were used to estimate the NI that generates images at a noise equal to images obtained with protocol A. This NI is designated hereafter as ATCM-reference NI (NIATCM).

CNR, CNR, and CNR were calculated at all NIs. Polynomial fits of CNR, CNR, and CNR versus NI were generated. The fitting parameters were used to estimate the CNR, CNR, and CNR values for the \( \text{NI}_{\text{ATCM}} \) determined previously. These values are designated hereafter as \( \text{CNR}_{\text{ATCM}} \), \( \text{CNR}_{\text{ATCM}} \), and \( \text{CNR}_{\text{ATCM}} \), respectively.

To calculate the percent radiation dose difference between protocols A and B (%\( \text{D}_{\text{AB}} \)), the following equation was applied:

\[
\% \text{D}_{\text{AB}} = \frac{\text{CTDIvol}_A - \text{CTDIvol}_B}{\text{CTDIvol}_A} \times 100\% \quad (1)
\]

where \( \text{CTDIvol}_A \) is the CTDIvol value prescribed by protocol A, and \( \text{CTDIvol}_B \) is the CTDIvol prescribed by protocol B at \( \text{NI}_{\text{ATCM}} \).
Protocol C: The Effect of ATVS on Reference NI and Reference Radiation Dose

CNRi versus NI in CTA, CNRiB versus NI in BONE, CNRi versus NI in C+, and CNRiST versus NI in C− were calculated at all NIIs. Polynomial fits of NI versus CNRi, CNRiB, and CNRiST were generated. The fitting parameters were used to estimate the NI for the CNRiRef, CNRiBRef, and CNRiSTRef values described previously. These NIIs are designated hereafter as ATVS-reference NI for “CTA” (NIATVSCTARef), “Bone” (NIATVSBoneRef), “C+” (NIATVSC+Ref), and “C−” (NIATVSC−Ref). At each clinical mode, polynomial fits of CTDIvol versus NI were generated. The fitting parameters were used to estimate the CTDIvol at the ATVS-reference NI values described previously.

To calculate the percent dose difference between protocols A and C (%DAC), the following equation was applied:

$$%D_{AC} = \frac{A_{CTDI_{vol}} - C_{(CTDI_{vol})_{NI_{ATVSRef}}}^{kVP}}{A_{CTDI_{vol}}} \times 100\%$$

where \(C_{(CTDI_{vol})_{NI_{ATVSRef}}}^{kVP}\) is the CTDIvol prescribed by protocol C at the ith clinical mode, and kVp, \(NI_{ATVSRef}\) values that generate images of a similar CNR to images with protocol A.

Statistical Analysis

Noise Index was linearly correlated to image noise. Association between CNR and NI and between CTDIvol and NI was determined using polynomial fitting. Correlation coefficients and P values were used to evaluate goodness of fit. All statistical computations were processed using MedCalc software package (MedCalc Software, Ostend, Belgium).

RESULTS

Protocol A

Measured image noise in acquisitions with protocol A ranged across phantoms from 3.93 to 7.08 for head, 6.55 to 10.95 for thorax, and 6.82 to 10.56 for abdomen/pelvis. A CTDIvol ranged from 15.12 mGy to 46.26 mGy for head, 1.89 mGy to 4.53 mGy for thorax, and 3.21 mGy to 5.22 mGy for abdomen/pelvis (Table 3).

Protocol B

Measured image noise correlated strongly with NI across all phantoms and anatomical regions. Calculated 15% CTDIvol recorded from acquisitions performed at NIATCMRef, ranged from 12.24 mGy to 57.59 mGy for head, 1.58 mGy to 2.76 mGy for thorax, and 1.88 mGy to 3.49 mGy for abdomen/pelvis (Table 4).

CNRi, CNRiB, and CNRiST correlated strongly and decreased with NI (Fig. 5, Table S2, Supplemental Digital Content, http://links.lww.com/RLI/A419). These fitting parameters were used to estimate ATCM-reference NI (NIATCMRef) for protocol B across all phantoms and anatomical regions, which generate images with similar noise to protocol A.

![Graph shows user-selected NI versus measured image noise for thorax of each phantom](http://links.lww.com/RLI/A419)

FIGURE 4. Graph shows user-selected NI versus measured image noise for thorax of each phantom. The linear fitting parameters between NI and image noise (\(a_i/b_i\)) and correlation coefficient (\(R^2\)) are shown in Table 5, Supplemental Digital Content, http://links.lww.com/RLI/A419. These fitting parameters were used to estimate ATCM-reference NI (NIATCMRef) for protocol B across all phantoms and anatomical regions, which generate images with similar noise to protocol A.

| Age, y | Head | Thorax | Abdomen/Pelvis |
|--------|------|--------|----------------|
| Neonate| Image noise | 5.20 | 6.55 | 6.82 |
| 1      | CTDIvol | 15.12 | 4.53 | 5.22 |
| 5      | Image noise | 5.19 | 7.61 | 9.77 |
| 10     | Image noise | 4.62 | 3.43 | 4.66 |

Where CTDIvol values have been downscaled to take into account that images were reconstructed using the ASIR algorithm. Results are presented for each phantom and anatomical region.

![Measured Image Noise (SD)](http://links.lww.com/RLI/A419)

TABLE 3. Measured Mean Image Noise and Corresponding A CTDIvol for Reference Examination Protocol (Protocol A)

| Age, y | Head | Thorax | Abdomen/Pelvis |
|--------|------|--------|----------------|
| Neonate| Image noise | 5.20 | 6.55 | 6.82 |
| 5-year-old| Image noise | 15.12 | 4.53 | 5.22 |
| 10-year-old| Image noise | 5.19 | 7.61 | 9.77 |
| 10-year-old| Image noise | 4.62 | 3.43 | 4.66 |

Where CTDIvol values have been downscaled to take into account that images were reconstructed using the ASIR algorithm. Results are presented for each phantom and anatomical region.

![Measured Image Noise (SD)](http://links.lww.com/RLI/A419)

TABLE 4. Calculated NIATCMRef Using the aT/bT Fitting Parameters of Table S1, Supplemental Digital Content, http://links.lww.com/RLI/A419, and Corresponding A CTDIvol for ATCM-Activated Protocol (Protocol B)

| Age, y | Head | Thorax | Abdomen/Pelvis |
|--------|------|--------|----------------|
| Neonate| NIATCMRef | 5.81 | 11.61 | 10.63 |
| 5-year-old| NIATCMRef | 13.90 | 2.76 | 3.19 |
| 10-year-old| NIATCMRef | 7.70 | 11.68 | 11.11 |
| 10-year-old| NIATCMRef | 12.24 | 1.58 | 1.88 |
| 5-year-old| NIATCMRef | 5.14 | 10.74 | 11.03 |
| 10-year-old| NIATCMRef | 30.92 | 2.04 | 2.59 |
| 10-year-old| NIATCMRef | 3.86 | 13.11 | 12.46 |

Results are presented for each phantom and anatomical region.
Protocol C

User-selected NI in protocol C correlated strongly and decreased with CNRI, CNRB, and CNRST at all clinical modes, and across all phantoms and anatomical regions (Fig. 6 and Table S3, Supplemental Digital Content, http://links.lww.com/RLI/A419). Calculated NIATVS\_CTA; Ref, NIATVS\_BONE; Ref, NIATVS\_C\_+; Ref, and NIATVS\_C\_−; Ref values that generate images of similar contrast to corresponding acquisitions of protocol B, are reported in Table 7. These values were calculated using the αk,bk, fitting parameters of Table S3, Supplemental Digital Content, http://links.lww.com/RLI/A419, and the CNR\_Ref, CNR\_B, and CNR\_ST values of Table 5.

The ATVS-recommended kVp at each clinical mode varied on the user-selected NI. The ATVS-recommended kVp at the NIATVS\_CTA; Ref, NIATVS\_BONE; Ref, NIATVS\_C\_+; Ref, and NIATVS\_C\_−; Ref values of Table 7 are reported in Table 8. In neonate, 80 kVp was recommended at all clinical modes and anatomical regions. In 1-year-old, 80 kVp was recommended most often, whereas 100 kVp was recommended in C\_+ and C\_− of head and abdomen/pelvis. In 5-year-old, 100 kVp was recommended most often, whereas 120 kVp was recommended in C\_+ and C\_− of head. In 10-year-old, 100 kVp was recommended in CTA, BONE, and C\_+ of thorax and abdomen/pelvis, and 120 kVp was recommended at all clinical modes of head and C\_− of thorax and abdomen/pelvis.

CTDI\_vol in protocol C correlated strongly and decreased with NI at all clinical modes, and across all phantoms and anatomical regions (Fig. 7 and Table S4, Supplemental Digital Content, http://links.lww.com/RLI/A419). These αM,bM fitting parameters were used to calculate the C\_CTDI\_vol (kVp)NIATVS\_i; Ref at the ATVS-reference NI (Table 9). In CTA, calculated C\_CTDI\_vol (kVp)NIATVS\_CTA; Ref ranged from 7.86 to 33.54 mGy for head, 0.61 to 1.26 mGy for thorax, and 0.87 to 2.67 mGy for abdomen/pelvis. In BONE, calculated C\_CTDI\_vol (kVp)NIATVS\_BONE; Ref ranged from 11.79 to 52.27 mGy for head, 0.88 to 1.69 mGy for thorax, and 0.69 to 2.21 mGy for abdomen/pelvis. In C\_+, calculated C\_CTDI\_vol (kVp)NIATVS\_C\_+; Ref ranged from 10.66 to 33.07 mGy for head, 0.54 to 1.47 mGy for thorax, and 0.85 to 2.57 mGy for abdomen/pelvis. In C\_−, calculated C\_CTDI\_vol (kVp)NIATVS\_C\_−; Ref ranged from 15.87 to 55.97 mGy for head, 1.57 to 3.71 mGy for thorax, and 1.67 to 3.86 mGy for abdomen/pelvis.

**TABLE 5.** Calculated CNR\_I\_Ref, CNR\_B\_Ref, and CNR\_ST\_Ref Using the αk,bk Fitting Parameters of Table S2, Supplemental Digital Content, http://links.lww.com/RLI/A419, for ATCM-Activated Examination Protocol (protocol B)

| Age, y | Head | Thorax | Abdomen/Pelvis |
|-------|------|--------|---------------|
| Neonate | 43.4/120.1/6.1 | 29.4/72/1.3/62 | 26.9/72/8.5/1 |
| 1 | 40.2/131.8/9.8 | 19.6/69/4.4/7 | 17.3/68.5/6.2 |
| 5 | 35.2/190.1/19.4 | 21.3/76/2.5/5.5 | 23.3/76/2.3/71 |
| 10 | 43.9/223/23.3 | 15.9/70/6.5/1 | 18.6/41/8.5/9 |

Results are presented for each phantom and anatomical region.

**TABLE 6.** Percent Dose Difference (%D\_AB) Between Reference Examination Protocol (Protocol A) and ATCM-Activated Acquisitions (Protocol B) for Each Phantom and Anatomical Region

| Age, y | Head | Thorax | Abdomen/Pelvis |
|-------|------|--------|---------------|
| Neonate | 8.0% | 39% | 39% |
| 1 | 19% | 16% | 41% |
| 5 | 21% | 29% | 25% |
| 10 | 24% | 38% | 25% |

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FIGURE 6. Protocol C: Graph shows user selected NI versus CNR, for CTA, CNR, for BONE, CNR, for C+ and CNR, for C− clinical mode in thorax ATVS-activated acquisitions of the 5-year-old phantom. Association between NI and CNR was determined using polynomial fitting as

\[ NI = \alpha K/C2 - bK. \]

\[ \alpha K/bK, R^2 \text{ fitting parameters for all phantoms, and anatomical regions are tabulated in Table S3, Supplemental Digital Content, http://links.lww.com/RLI/A419.} \]

**TABLE 7.** Calculated \(NI_{\text{ATVS}}\) \(\text{CTA/Re}f\), \(NI_{\text{ATVS}}\) \(\text{BONE/Re}f\), \(NI_{\text{ATVS}}\) \(\text{C+/Re}f\) and \(NI_{\text{ATVS}}\) \(\text{C−/Re}f\) Values That Generate Images of Similar Contrast to Protocol B

| Age, y | Head | Thorax | Abdomen/Pelvis |
|-------|------|--------|----------------|
|        | \(NI_{\text{CTA/Re}f}\) | \(NI_{\text{BONE/Re}f}\) | \(NI_{\text{C+/Re}f}\) | \(NI_{\text{C−/Re}f}\) |
| Neonate | 8.25/7.17/8.18/7.63 | 13.09/11.29/12.55/8.98 | 11.76/9.86/14.60/9.60 |
| 1 | 8.22/8.89/9.87/9.70 | 13.02/11.65/15.76/10.82 | 11.88/10.11/13.81/11.20 |
| 5 | 7.22/7.25/7.99/6.83 | 11.09/10.29/12.26/11.11 | 11.21/10.53/14.1/10.32 |
| 10 | 8.19/5.19/8.18/6.61 | 12.94/12.31/14.38/11.85 | 11.69/18.54/11.11/9.77 |

These values were calculated using the \(a_k\), \(b_k\), fitting parameters of Table S3, Supplemental Digital Content, http://links.lww.com/RLI/A419, at \(\text{CNR}_{\text{Ref}}\), \(\text{CNR}_{\text{B}}\), \(\text{CNR}_{\text{ST}}\) values of Table 5.

**TABLE 8.** ATVS-Recommended kVp in ATVS-Activated Acquisitions at Each Clinical Mode and at the \(NI_{\text{ATVS}}\) \(\text{CTA/Re}f\), \(NI_{\text{ATVS}}\) \(\text{BONE/Re}f\), \(NI_{\text{ATVS}}\) \(\text{C+/Re}f\) and \(NI_{\text{ATVS}}\) \(\text{C−/Re}f\) Values of Table 7 Across All Phantoms and Anatomical Regions

| Age, y | Head \(\text{CTA/BONE/C+/C−}\) | Thorax \(\text{CTA/BONE/C+/C−}\) | Abdomen/Pelvis \(\text{CTA/BONE/C+/C−}\) |
|-------|-----------------|-----------------|-----------------|
| Neonate | 80/80/80/80 | 80/80/80/80 | 80/80/80/80 |
| 1 | 80/80/100/100 | 80/80/80/80 | 80/80/100/100 |
| 5 | 100/100/120/120 | 100/100/100/100 | 100/100/100/100 |
| 10 | 120/120/120/120 | 100/100/100/120 | 100/100/100/120 |
with contrast-enhanced studies. Thus, the \( kVp \) and NI settings recommended for examinations, the tolerated image noise might be even less compared to a dose increase of up to 21\% for head and a dose reduction between CTDI\(_{\text{vol}}\) and Noise Index was determined using polynomial fitting as \( NI = a_M \times \text{CNR}^{-b_M} \). \( a_M/\text{INB} \) \( R^2 \) fitting parameters for all phantoms, and anatomical regions are tabulated in Table S4, Supplemental Digital Content, http://links.lww.com/RLI/A419.

In contrast-enhanced soft tissue examinations, such as chest or portal venous phase abdominal CT, detection and characterization of tissue lesions require a lower noise level compared with CTA studies. C+ resulted to a dose reduction of up to 46\% for head, 71\% for thorax, and 79\% abdomen/pelvis. For thorax, and abdomen/pelvis result to a lower dose reduction compared with contrast-enhanced studies. It is not known, however, why dose was increased in head acquisitions. Possible explanation might be that increased modulated mA values are required in that clinical mode to counterbalance the low inherent \( \text{CNR}_{\text{ROI}} \) in the brain. This merits further clinical investigation into whether ATCM might be applicable to pediatric noncontrast head CT examinations.

Several studies have demonstrated the advantages of using ATVS in body CT examinations of adult patients. Spearman et al.\(^{13}\) on a multicenter study have shown that ATVS reduces radiation exposure by up to 56\% in temporal bone CT and that dose reduction is profound in CT angiographic studies. Layritz et al.\(^{17}\) have shown that the use of ATCM in coronary CTA reduces radiation dose by 39\%, and Lee et al.\(^{12}\) have reported that the use of ATCM and ATVS in contrast-enhanced liver CT of adults reduce radiation dose by up to 31\%. In a study performed by Siegel et al.\(^{22}\) on the effect of ATVS on radiation dose in pediatric contrast-enhanced thoracoabdominal CT, a dose reduction of 27\% has been reported. Furthermore, Siegel et al.\(^{21}\) have used 3 small-sized semianthropomorphic phantoms to investigate the effect of ATVS on radiation dose in pediatric abdominal CTA examinations. Radiation dose was reduced by 31\%, 36\%, and 44\% for the small, medium, and large phantoms, respectively. The above studies have been reporting results using an ATVS system available from a single only vendor (Siemens Healthcare). To our knowledge, scarce data are available on the use of ATVS used by other CT vendors. Li et al.\(^{18}\) have recently shown that ATVS in contrast-enhanced adult chest CT examinations results to a dose reduction of 31\% without affecting image quality. Another important approach to reduce pediatric radiation dose is tin filtering. Weis et al.\(^{24}\) have suggested that the use of additional tin filtering at 100 kVp significantly reduces radiation dose compared with 70 kVp and therefore should be preferred in non–contrast-enhanced pediatric chest CT, particularly when the main focus is evaluation of lung parenchyma.

A major contribution of this work is that we have determined the \( N_{\text{Ref}}^{\text{ATCM}} \) values in ATCM-activated acquisitions that produce images of comparable noise to the images derived from the REPs (Table 4). To our knowledge, there is no published data on the effect of ATCM, which is based on the NI concept, on radiation dose, and image quality in pediatric CT. In NI-based ATCM, a higher NI will generate images of more noise, and CT acquisition will be performed at a lower mA, whereas a lower NI will generate images of less noise, and CT acquisition will be performed at a higher mA compared with the REP. Computed tomography operators may use the \( N_{\text{Ref}}^{\text{ATCM}} \) values of Table 4 to generate images at a comparable noise and at a substantially reduced dose compared with the corresponding REP (Table 6).

One further major contribution of this work is that we have determined the \( N_{\text{Ref}}^{\text{ATVS}} \) in ATVS-activated acquisitions that produce images of comparable CNR to the images derived from the REPs (Table 7). \( N_{\text{Ref}}^{\text{ATVS}} \) values are proposed for each clinical imaging diagnostic task. When CT operators are asked to activate ATVS for a specific diagnostic task, they should input a \( N_{\text{Ref}}^{\text{ATVS}} \) value. To our knowledge, there is no published data on what NI values should operators use in ATVS-activated

### Table 9: Calculated \( C(\text{CTDI}_{\text{vol}}) \) at \( N_{\text{Ref}}^{\text{ATCM}} \) and \( N_{\text{Ref}}^{\text{ATVS}} \)

|        | Head | Thorax | Abdomen/Pelvis |
|--------|------|--------|---------------|
| Age, y | \( C(\text{CTDI}_{\text{vol}}) \) | \( N_{\text{Ref}}^{\text{ATCM}} \) | \( N_{\text{Ref}}^{\text{ATVS}} \) |
| Neonate | 7.86/11.79/10.66/15.87 | 1.02/1.55/1.47/3.71 | 1.24/2.01/1.07/3.19 |
| 1      | 13.24/12.94/13.01/16.53 | 0.61/0.88/0.54/1.57 | 0.87/1.37/0.85/1.67 |
| 5      | 33.54/33.58/33.07/43.80 | 1.24/1.68/1.25/1.87 | 1.69/2.21/1.19/2.97 |
| 10     | 13.54/52.27/24.99/55.97 | 1.26/1.69/1.30/2.53 | 2.67/0.69/2.57/3.86 |
acquisitions of pediatric CT. Moreover, there is no published data on the effect of $N_{ATS}$ on radiation dose and image quality for different clinical diagnostic tasks. Computed tomography operators may use the $N_{ATS}$ (Table 7) to generate images at a comparable CNR and at substantially reduced dose compared with the REP (Table 10).

One limitation of this study was that we did not verify our results in the clinical practice. However, it is not feasible to perform repetitive exposures to the same patient because of ethical issues. Moreover, a large number of patients are required to cover ages from newborns to adolescents to make interindividual comparisons. The physical anthropomorphic phantoms used herein facilitate the investigation of the effect of acquisition parameters on image quality and radiation dose in the same subject without considering ethical issues. Moreover, image quality was assessed only on the basis of objective quality measures. A subjective evaluation of the image quality from experienced radiologists would add useful input on the verification of the proposed $NT_{ATCM}$ and $N_{ATS}$ values. Scanning at 70 kVp has also been shown to reduce pediatric radiation dose compared with 80 kVp. However, the technology of the scanner used herein did not allow acquisition at this tube potential. The results presented herein refer to a single vendor and 4 clinical diagnostic tasks. It would be very interesting to apply the methodology presented in this study on scanners developed by other CT manufacturers and on more clinical diagnostic settings.

In conclusion, we have shown that the use of ATCM in pediatric head and torso CT reduces radiation dose without impairing image noise. The use of ATVS for a specified clinical diagnostic task reduces further radiation dose without impairing CNR. We suggest that ATCM should be activated in all pediatric examinations. Moreover, ATVS should be activated in all but noncontrast examinations. The current results highlight the importance of using the ATCM and ATVS tools in the clinical routine for dose optimization in pediatric CT.

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# TABLE 10. Percent Dose Difference ($\%D_{AC}$) Between Reference Examination Protocol (Protocol A) and ATVS-Activated Acquisitions (Protocol C) for Each Phantom and Anatomical Region

| Age, y | Head | Thorax | Abdomen/Pelvis |
|-------|------|--------|----------------|
|       | CTA/BONE/C+/C− | %D<sub>AC</sub> | CTA/BONE/C+/C− | %D<sub>AC</sub> | CTA/BONE/C+/C− | %D<sub>AC</sub> |
| Neonate | 48%±22%/29%/−−5% | 77%/66%/67%/16% | 76%/61%/79%/39% | 68%/53%/71%/17% | 73%/57%/73%/48% | 57%/41%/56%/34% | 51%/36%/65%/14% | 63%/51%/62%/26% | 43%/85%/45%/17% |
| 1 | 12%/14%/14%/−−9% | 57%/41%/56%/34% | 51%/36%/65%/14% | 63%/51%/62%/26% | 43%/85%/45%/17% |
| 5 | 14%/14%/16%/−−12% | 57%/41%/56%/34% | 51%/36%/65%/14% | 63%/51%/62%/26% | 43%/85%/45%/17% |
| 10 | 70%/13%/46%−−21% | 63%/51%/62%/26% | 43%/85%/45%/17% |

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