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Original article

Quality control of clinical protocols using the CT accreditation phantom

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Abstract

Background: The daily quality control of the computed tomography (CT) system consists of measuring the accuracy of the CT number and artifact evaluation. The annual quality control includes a clinical protocol review. The quality assurance requirements are the responsibility of the CT radiologist, whereas the clinical team reviews and manages the CT protocol to deliver the appropriate radiation dose to the patient for each examination.
Objectives: This study aimed to examine CT number accuracy, review clinical protocols, and verify that the low-contrast performance of clinical protocols was adequate for diagnosis.
Methods: The American College of Radiology (ACR) CT accreditation phantom (CTAP) was scanned by five CT systems with four clinical protocols. The acquisition parameters for the four clinical protocols of each CT manufacturer were set according to the ACR CTAP standard criteria. The CT number calibration was performed, and the low contrast performance in terms of the contrast-to-noise ratio (CNR) was quantitatively evaluated.
Results: The mean CT numbers of polyethylene, acrylic, water, bone, and air were –96, 125, 0, 919, and –993 Hounsfield Unit (HU), respectively. The CNR of the adult brain protocol from the five CT systems was 1.6, 1.8, 1.9, 2.5, and 2.2, and the pediatric brain protocol was 1.5, 1.1, 1.1, 1.1, and 2.0, respectively. The CNR of the adult abdomen protocol was 1.1, 1.1, 1.1, 1.3, and 1.0, and the pediatric abdomen protocol was 0.5, 0.5, 0.5, 1.1, and 0.4, respectively.
Conclusion: The CT numbers in HU were within the calibration criteria for polyethylene (–107 to –84), acrylic (110 to 135), water (–7 to 7), bone (850 to 970), and air (–1005 to –970). The CNR of four clinical protocols were within the ACR Guidelines of the adult head >1.0, pediatric head >0.7, adult abdomen >1.0, and pediatric abdomen >0.4.

Keywords: ACR CT accreditation phantom**,** annual quality control, contrast-noise ratio, low-contrast performance, quality control of clinical protocols.

Computed tomography (CT) is a medical imaging method that has been used worldwide since its invention by Sir Godfrey Hounsfield in 1970. However, considerable variability in the image quality of CT performed at different sites was observed. The American College of Radiology (ACR) (1) has initiated a voluntary CT accreditation program to establish practices and standards for quality control (QC), including dose and image quality. (2) Optimization of patient dose reduction and appropriate image quality is one part of the QC of CT scans. Furthermore, a review of clinical protocols will avoid inappropriate patient doses as a focus of continuous quality assurance. (3) An effective QC program will potentially identify problems before they seriously affect clinical results.

To verify that a CT scanner performs consistently and yields acceptable image quality (4), a set of QC tests is required. If the CT scanner fails the test, further investigation is recommended to determine the cause of the failure. Therefore, clinical protocols with appropriate acquisition parameters, including kilovolt, milliampere-second, detector configuration, reconstructed scan width, pitch, reconstruction algorithm, and other features, such as dose reduction

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options, automatic exposure controls, and iterative reconstruction techniques, will be selected. Moreover, this ensures that these protocols provide adequate diagnostic image quality for the CT exam while minimizing the radiation dose to the patient. Therefore, the use of the American Association of Physicists in Medicine (AAPM) medical physics practice guideline and the AAPM CT protocol management and review practice guideline is recommended. [5]

The objectives of this study were to review the clinical protocols, verify the accuracy of the CT numbers, and study the low-contrast performance of four clinical protocols for the brain and abdomen of adults and pediatrics.

Materials and methods

ACR CT accreditation phantom (CTAP)

The ACR CTAP [6] is a water-equivalent phantom of four modules, as shown in **Figure 1. (A)** Each module is 4 cm in depth and 20 cm in diameter; **(B)** There are external alignment markings scribed and painted white on each module to allow centering of the phantom [6] along the axial (z-axis, cranial/caudal), coronal (y-axis, anterior/posterior), and sagittal (x-axis, left/right) directions. [7] There are "HEAD," "FOOT," and "TOP," markings on the phantom to assist with positioning **(B).**

The ACR CT accreditation phantom has been designed to examine a broad range of scanner parameters, including four modules as shown in **Figure 1.** Module 1 is a water equivalent as the background material. It is used to check the positioning and alignment, CT number accuracy, and slice thickness. For positioning, the module has 1-mm diameter steel embedded at the longitudinal (z-axis) center of the module, with the outer surface of the steel at the phantom surface at the 3, 6, 9, and 12 o'clock positions within the field of view (19.9 cm center to center). To assess the accuracy of the CT number, four cylinders of different materials (bone material ("Bone"), polyethylene, acrylic, and air) each have a diameter of 25 mm and a depth of 4 cm. The water-equivalent cylinder has a diameter of 50 mm and a depth of 4 cm, as shown in **Figure 2.**

Module 2 is used to assess the low contrast resolution. This module consists of a water-equivalent cylinder background with a series of cylinders of different diameters, with a mean CT number of approximately 90 Hounsfield Unit (HU). The cylinder-to-background contrast is energy-independent. There are four cylinders for each of the following diameters: 2, 3, 4, 5, and 6 mm. The space between each cylinder is equal to the diameter of the cylinder. A 25-mm cylinder is included to verify the cylinder-to-background contrast level and assess the contrast-to-noise ratio (CNR) (**Figure 3**).

Module 3 consists of a uniform, tissue-equivalent material to assess CT number uniformity. Two small steel (0.3 mm each) are included for optional use in assessing the accuracy of in-plane distance measurements at 100 mm separation (**Figure 4**). These are also used to assess section sensitivity profiles.

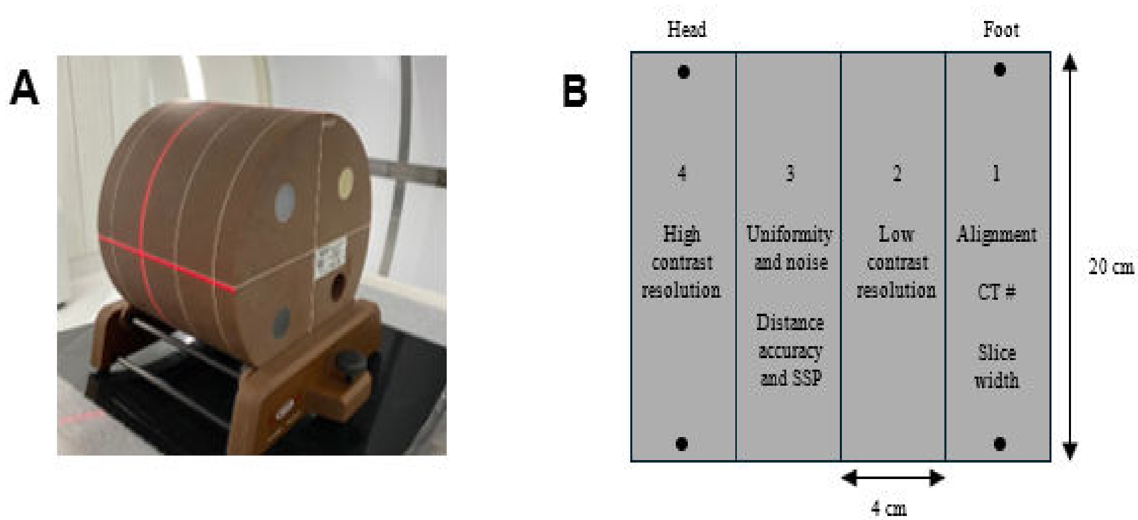

Figure 1. (A) ACR CT accreditation phantom; **(B)** diagram of 4 modules.

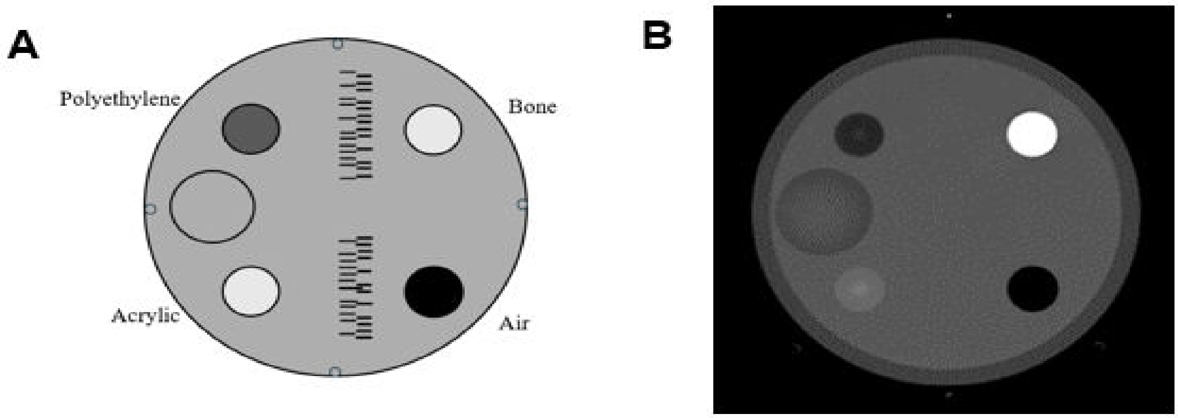

Figure 2. Module 1 position and alignment, CT number accuracy, and slice thickness assessment. **(A)** water equivalent phantom with cylinders of different materials, diameters and CT numbers**; (B)** cross sectional image for CT number accuracy assessment.

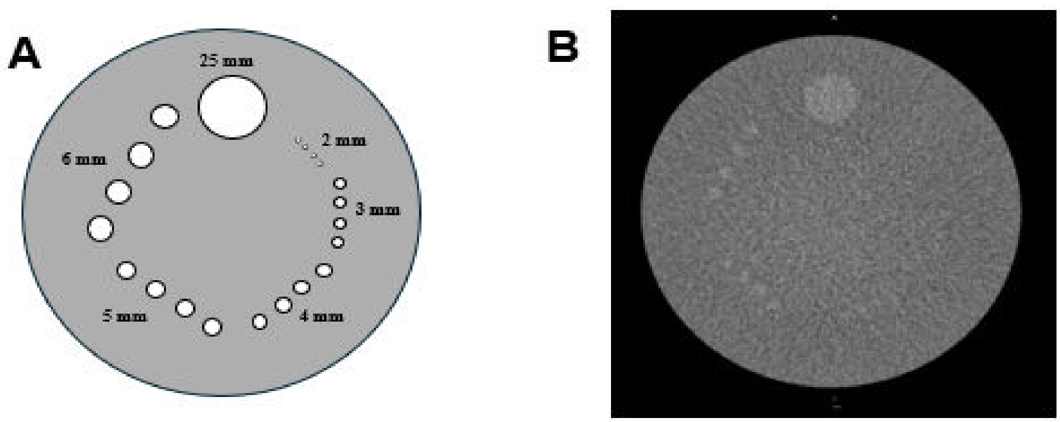

Figure 3. Module 2: Low contrast resolution assessment; **(A)** water equivalent phantom with cylinders diameter 2, 3, 4, 5, and 6 mm; **(B)** cross sectional image for low contrast resolution assessment.

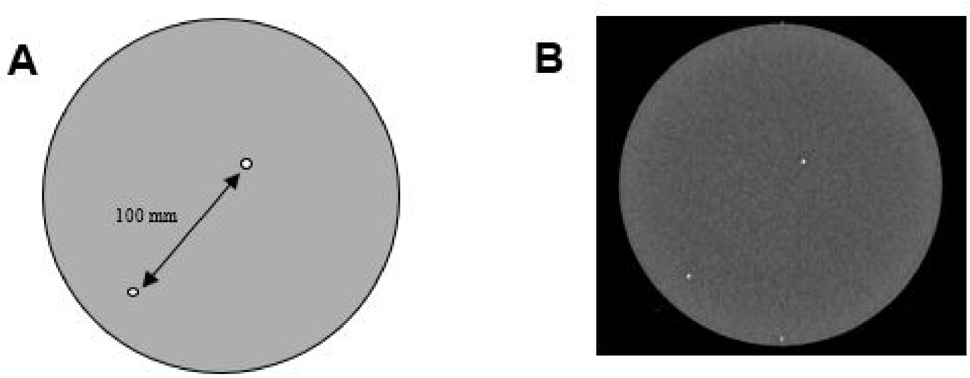

Figure 4. Module 3: CT number uniformity assessment. **(A)** water equivalent phantom; **(B)** cross sectional image for uniformity assessment.

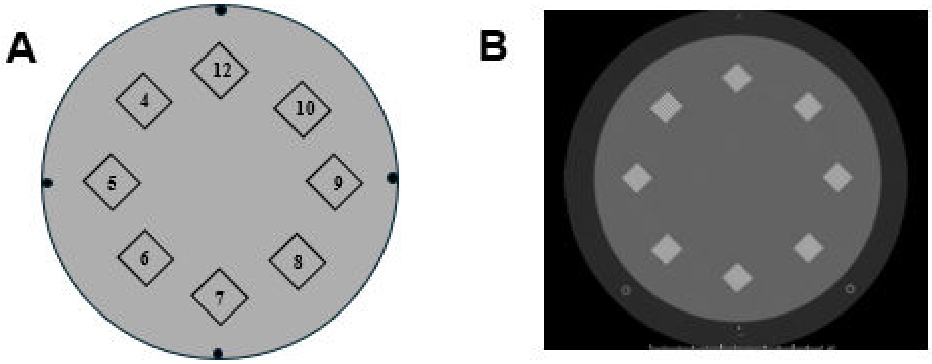

Figure 5. Module 4: High contrast resolution assessment**. (A)** water equivalent phantom with 8 bar resolution; **(B)** cross sectional image for high contrast resolution measurement.

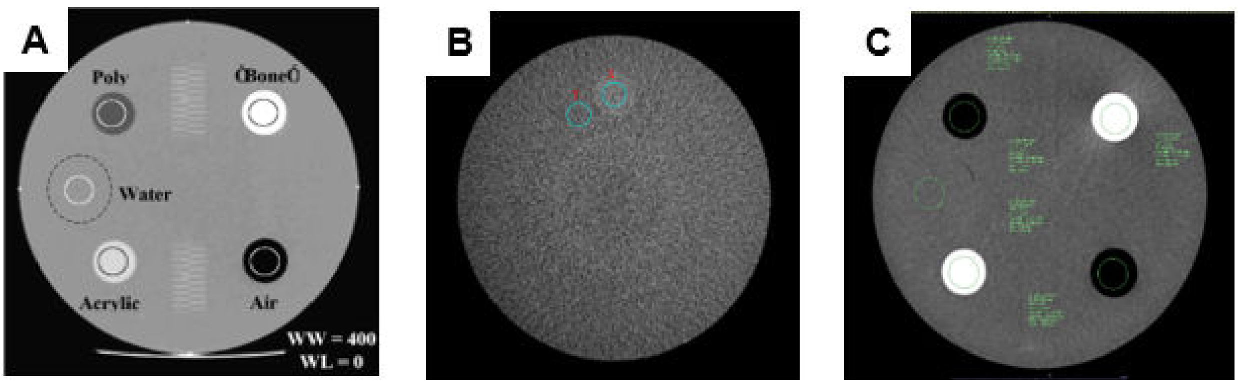

Figure 6. (A) Regions of interest (ROIs) for four materials, polyethylene, bone, air and acrylic and the water-equivalent background material; **(B)** Module 2 low contrast resolution image at WW, 100 and WL, 100 with correct ROI placements at X, signal, and Y, background; **(C)** CT number measurement of 4 materials and the water-equivalent background material.

Module 4 is used to assess the high-contrast spatial resolution. The water-equivalent background contains eight bar resolution patterns with 4, 5, 6, 7, 8, 9, 10, and 12-line pair/cm, each fitting into a 15 -mm × 15 mm square region, as shown in **Figure 5.** The z-axis depth of each bar pattern is 3.8 cm, beginning at the Module 3 interface. The aluminum bar patterns provide a high object contrast relative to the background material. Module 4 also has four 1 mm steel beads, as described for Module 1 [6] and displayed in **Figure 1B.**

Methods

The ACR CTAP was scanned using four clinical protocols of adult abdomen, adult head, pediatric abdomen, and pediatric head with five CT systems at King Chulalongkorn Memorial Hospital, Thai Red Cross Society. The manufacturer, model, and year of installation of these CT systems are as follows: 1) GE Revolution Apex, 2022; 2) GE Revolution CT EX, 2018; 3) GE Discovery 750HD, 2012; 4) Siemens Somatom Force, 2015; and 5) Philips Incisive, 2020.

The four clinical protocols with the scan methods are as follows: 1) Adult abdomen: Scan the phantom with the average adult abdomen protocol. Enter the average technique used for a mid-liver image of an average-sized patient; 2) Adult head: Enter the average parameters used in the protocol for the cerebrum portion of the adult brain; 3) Pediatric abdomen: For the chest and/or abdomen modules of pediatric patients, enter the average mid-liver protocol for a pediatric abdomen examination on a 20 kg child; and 4) Pediatric head: Enter the average parameters used in the protocol for the cerebrum portion of a pediatric brain for a 1-year-old child.

The average tube current (mA) was calculated from the dose monitoring software according to the patient's age or body weight. A) adult head (average); B) pediatric head (1-year-old); C) adult abdomen (70 kg); and D) pediatric abdomen (5 years old; 40–50 lb, approximate 20 kg). ACR recommends the use of manual mA rather than auto mA. For the abdomen, mid-liver positioning is used, and for the brain, cerebrum positioning is used.

Evaluating the ACR CTAP images

Using the obtained images from scanning the phantom with the protocols listed for the phantom data, the images are evaluated for pass/fail criteria. The best images from each scan series for each phantom module should be used. The method and criteria for the measurements are the CT number calibration and low contrast criteria (CNR), respectively. [8]

CT number calibration

View the best Module 1 image scanned using the adult abdomen protocol. Place a circular region of interest (ROI, approximately 200 mm^2) within each cylinder **(Figure 6)** and record the mean CT number for each material. It is important to center the ROIs within each cylinder. The water cylinder is seen subtly as a large gray ring. The water ROI is drawn as shown in **Figure 6A.** The mean CT number of the five materials is measured, and compared to the results of the CT number calibration criteria. Values outside of the HU criteria result in a minor deficiency. [9]

Low contrast criteria (CNR)

View the best image located in Module 2 for all protocols using a window width of 100 and window level of 100. There are four cylinders for each of the following diameters: 2, 3, 4, 5, and 6 mm (**Figure 6B**). Place an ROI (X) of 100 mm^2 over the large (25-mm diameter) cylinder and between the large cylinder and 6 mm cylinders as the background ROI (Y).

Record the mean signal and CT number of the ROI inside the 25 mm rod (X); the mean signal and CT number of the ROI outside the 25 mm rod (Y); and the standard deviation (SD) and CT number of the ROI outside the 25 mm rod. Use the following formula to calculate the CNR:

$$CNR = |X-Y|/SD$$

Use the absolute value of the difference, i.e., **do not** take into consideration whether the CNR is a positive or negative number. The CNR must be > 1.0 for the adult head and adult abdomen protocols. The CNR must be >0.4 for the pediatric abdomen protocol and > 0.7 for the pediatric head protocol. CNR values below the listed criteria will result in a minor deficiency.

Results

CT number accuracy

The circular ROI has an approximate area of 230 mm^2, a perimeter of 54 mm, and was created from different objects of polyethylene, water, acrylic, bone, and air in the ACR (CTAP) Module 1 **(Figure 6C).** The mean CT numbers of the five objects were –96, 0, 125, 919, and –993, respectively. The results of the mean CT number were compared to the CT number calibration criteria to check the CT number accuracy, as shown in **Table 1**. All the mean CT number values were within the range and passed the calibration criteria. Values outside each of the listed criteria will result in a minor deficiency. [9]

Table 1. Measured mean CT number *vs.* CT number calibration criteria. CT, computed tomography; HU, Hounsfield Unit.

Materials	Measured CT number (mean), HU	CT number calibration criteria, HU	Pass / minor deficiency
Polyethylene	- 96	- 107 to - 84	Pass
Water	0	- 7 to + 7	Pass
Acrylic	125	110 to 135	Pass
Bone	919	850 to 970	Pass
Air	- 993	- 1005 to - 970	Pass

Review four CT clinical protocols for 5 CT systems using ACR CTAP

The acquisition parameters for the four clinical protocols of each CT manufacturer and model were recorded using the Radimetrics™ Enterprise Platform (Bayer HealthCare, Whippany, NJ, USA). [10] Dose monitoring software was used according to the ACR (CTAP) standard criteria. Two types of reconstruction methods of iterative reconstruction (IR) and deep learning (DL) are shown in **Table 2** to **5.**

After reviewing the four clinical protocols of each CT system, the Gammex Model 464 (S.N. 804882-4364)—as an example—was used to perform the scanning of the ACR (CTAP) with the technique detailed in **Table 2** to **5**, and the CNR was calculated from the equation:

CNR = (target mean – background mean)/(SD background)

The results of the CNR calculation are displayed in **Table 6** and **7.**

Table 2. Parameters for 5 CT systems of brain clinical protocol without contrast in adults with dose.

Manufacturer model	GE revolution APEX	GE revolution CT EX	GE discovery 750 HD	Siemens Somatom force	Philips incisive
Scan type	Helical	Helical	Helical	Helical	Helical
Rotation time (sec)	0.5	0.5	0.8	1	0.5
Pitch	0.5 : 1	0.5 : 1	0.5 : 1	0.6	0.4
Slice thickness (mm) for measure CNR	5	5	5	5	5
kV	120	120	120	120	120
mA	330	320	170	240	280
IR/DL	DL-M	DL-M	AR30	SAFIRE 3	iDose 2
Beam collimation (mm)	0.6 × 64	0.6 × 64	0.6 × 32	0.6 × 192	0.6 × 64
$CTDI_{vol}$ (mGy)	49.0	46.9	51.1	62.3	49.4

Table 3. Parameters for 5 CT systems of brain clinical protocol without contrast in 1 year old child with dose.

Manufacturer Model	GE revolution APEX	GE revolution CT EX	GE discovery 750 HD	Siemens somatom force	Philips incisive
Scan type	Axial (volume)	Axial (volume)	Helical	Helical	Helical
Rotation time,(sec)	0.5	0.5	0.5	1	0.5
Pitch	-	-	0.5 : 1	0.8	0.4
Slice thickness (mm) for measure CNR	5	5	5	5	5
kV	120	120	100	100	100
mA	335	290	200	145	255
IR/DL	DL-M	DL-M	SS30	SAFIRE 3	iDose 2
Beam collimation (mm)	0.6 × 256 160 mm	0.6 × 224 140 mm	0.6 × 32	0.6 × 192	0.6 × 64
$CTDI_{vol}$ (mGy)	21.1	18.2	21.9	16.1	22.0

Table 4. Parameters for 5 CT systems of adult abdomen clinical protocol without contrast (70 kg adult) with dose.

Manufacturer model	GE revolution APEX	GE revolution CT EX	GE discovery 750 HD	Siemens somatom force	Philips incisive
Scan type	Helical	Helical	Helical	Helical	Helical
Rotation time, (sec)	0.5	0.5	0.5	0.5	0.75
Pitch	1.0 : 1	1.0 : 1	1.5 : 1	0.6	1
Slice thickness (mm) for measure CNR	2.5	2.5	2.5	2	2
kV	120	120	120	120	120
mA	505	430	530	228	387
IR/DL	DL-L	DL-L	AR50	SAFIRE 3	iDose 3
Beam collimation (mm)	0.6 x 128	0.6 × 128	0.6 × 64	0.6 × 192	0.6 × 64
CTDIvol (mGy)	17.3	15.6	13.9	12.7	23.5

Table 5. Parameters for 5 CT systems of pediatric abdomen clinical protocol without contrast (5 year old; 20kg child) with dose.

Manufacturer model	GE revolution APEX	GE revolution CT EX	GE discovery 750 HD	Siemens somatom force	Philips incisive
Scan type	Helical	Helical	Helical	Helical	Helical
Rotation time, (sec)	0.5	0.5	0.4	0.5	0.5
Pitch	1.0 : 1	1.0 : 1	1.4 : 1	1.4	1
Slice thickness (mm) for measure CNR	2.5	2.5	2.5	2	2
kV	100	100	100	100	100
mA	160	210	250	350	160
IR/DL	DL-L	ASIR50	SS30	SAFIRE 3	iDose 3
Beam collimation (mm)	0.6 × 64	0.6 × 64	0.6 × 32	0.6 × 192	0.6 × 64
CTDIvol (mGy)	3.2	4.2	3.5	4.0	3.9

Discussion

The first evaluation of the CT number calibration and accuracy is the most important aspect to ensure the accuracy of CT performance to accurately identify several media inside the body, such as air in the lungs, soft tissue, bone, and lesions. It is recommended as daily QC that a CT technologist perform a scan using the water phantom. Moreover, annual QC is performed by medical physicists and includes the ACR CTAP phantom of five materials of polyethylene, water, acrylic, bone, and air to simulate the body's soft tissues and lesions and assess the CT number accuracy within the limit of acceptability.

The second study aims to obtain the appropriate acquisition parameters of five CT systems from different manufacturers and models for the four clinical protocols of the brain and abdomen in adults and children. The volume CT dose index ($CTDI_{vol}$) was recorded as an indicator of the patient doses. These parameters were available from the dose monitoring software.

The third study calculated the low contrast resolution from the ACR CTAP as an indicator of the CT systems' image quality. Module 2 of the ACR phantom was scanned, and the CNRs were calculated for the four clinical protocols to verify the low contrast resolution. ACR proposed the CNR criteria of > 1 for the adult brain and abdomen, > 0.4 for the pediatric abdomen, and > 0.7 for the pediatric brain as the acceptable limit. Proper acquisition parameters can lead to high CNR values to pass the evaluations. The probability of distinguishing a lesion from the background is higher for a high CNR than for a low CNR.

Table 6. CNR of 5 CT systems of adult brain and abdomen clinical protocol without contrast.

Manufacturer/ model	Mean signal	Mean background	SD background	CNR	ACR acceptable limit	Test result (pass/fail)
Adult brain clinical protocol without contrast						
GE revolution APEX	88.4	82.3	3.9	1.6	≥1	Pass
GE revolution CT EX	95.4	88.8	3.6	1.8	≥1	Pass
GE discovery750 HD	95.8	89.5	3.2	1.9	≥1	Pass
Siemens somatom force	96.4	90.3	2.5	2.5	≥1	Pass
Philips incisive	95.5	89.1	2.9	2.2	≥1	Pass
Adult abdomen clinical protocol without contrast						
GE revolution APEX	96.1	89.6	6.2	1.1	≥1	Pass
GE revolution CT EX	95.7	88.3	6.7	1.1	≥1	Pass
GE discovery750 HD	100.5	94.5	5.5	1.1	≥1	Pass
Siemens somatom force	95.9	89.0	5.3	1.3	≥1	Pass
Philips incisive	96.3	90.4	5.7	1.0	≥1	Pass

Table 7. CNR of 5 CT systems of pediatric brain and abdomen clinical protocol without contrast in One - year old child and in 5-year-old, 20 kg child.

Manufacturer/ model	Mean signal	Mean background	SD background	CNR	ACR acceptable limit	Test result (pass/fail)
Brain clinical protocol without contrast in one year old child						
GE revolution APEX	94.0	86.9	4.8	1.5	≥0.7	Pass
GE revolution CT EX	94.5	89.0	5.1	1.1	≥0.7	Pass
GE discovery 750 HD	80.9	75.2	5.3	1.1	≥0.7	Pass
Siemens somatom force	87.4	81.1	5.8	1.1	≥0.7	Pass
Philips incisive	86.7	79.8	3.5	2.0	≥0.7	Pass
Abdomen clinical protocol without contrast in 5 years old, 20 kg child						
GE revolution APEX	85.9	78.7	14.9	0.5	≥0.4	Pass
GE revolution CT EX	85.1	79.6	10.9	0.5	≥0.4	Pass
GE discovery 750 HD	81.8	76.3	10.7	0.5	≥0.4	Pass
Siemens somatom force	88.2	80.5	7.1	1.1	≥0.4	Pass
Philips incisive	89.0	82.0	17.5	0.4	≥0.4	Pass

Table 6 shows that the highest CNR values for the brain and abdomen clinical protocols in adults were 2.5 and 1.3, respectively, and were obtained using the Siemens Somatom Force. The highest CNR in the pediatric brain was 2.0 and was obtained using the Philips Incisive, and in the pediatric abdomen, it was 1.1 using the Siemens Somatom Force.

The highest $CTDI_{vol}$ for the adult brain was 62.3 mGy, while the others ranged from 46.9 to 51.1 mGy, and the lowest $CTDI_{vol}$ in the pediatric brain was 16.1 mGy using the Siemens Somatom Force. The lowest $CTDI_{vol}$ for the adult abdomen was 12.7 mGy using the Siemens Somatom Force, and the lowest $CTDI_{vol}$ for the pediatric abdomen was 3.2 using the GE Revolution Apex. As the brain has a low sensitivity to radiation in comparison to the abdomen, a 62.3 mGy dose obtained by the adult brain will not have much effect when compared to the highest $CTDI_{vol}$ of 46.9–51.1 mGy. In pediatric patients, radiation sensitivity is much higher than in adults, and the lowest $CTDI_{vol}$ in pediatrics should be considered. The lowest $CTDI_{vol}$ in the adult and pediatric abdomen is considered greatly favorable, as there are several radiosensitive organs within the abdomen.

The annual QC of the five CT systems using the ACR CTAP to ensure that the performances of the CT systems are acceptable under the standard criteria and without the application of automatic exposure control is recommended by the ACR. The image quality from the low contrast performance in terms of CNR was calculated for the five CT systems using four adult and pediatric clinical protocols. The low contrast criteria were evaluated using the parameters of four common clinical protocols of the brain and abdomen in adults and pediatrics as proposed by the ACR. All of the test results were within the ACR acceptable limits. The use of IR, DL, and artificial intelligence (AI) influences the image quality and interpretation by the radiologist. [11 - 13]

The image quality also depends on the quality of the diagnostic workstation. The radiological technologist performs QC on the monitor monthly, while the picture archiving and communication system administrator assesses the image quality of the workstation annually. If the workstation is of poor quality, then a poor diagnostic result may be obtained. Radiologists frequently use the function on the monitor to check the monitor image quality.

Even though the CNRs from the different CT systems were similar and within the acceptable criteria, the CT dose in terms of the $CTDI_{vol}$ is carefully considered as data from some of the manufacturers exhibited higher values. The optimization of radiation protection is planned for the patient dose reduction, and the image quality is maintained. The team of CT radiologists, qualified medical physicists, and the chief CT technologist should meet to create a proper optimization protocol. Currently, the use of AI [11] for image reconstruction and dose reduction always reveals images that are too smooth, which influences image interpretation. [12] The benefit for the patient must be greater than the hazard.

Mansour Z, *et al.* [14] studied the image quality of a CT scanner using the ACR phantom Module 2, and the qualitative results of four cylinders for each diameter of 2, 3, 4, 5, and 6 mm were visualized. Our study showed the calculated CNRs from four clinical protocols and five CT systems were within the ACR acceptable limits, as shown in **Table 6** and **7**. These results demonstrate that the appropriate parameters were selected while reviewing the clinical protocols. The image quality could be expressed both qualitatively and quantitatively.

The limitation of the study is that only four of the six clinical protocols were studied. The other two clinical protocols recommended by the AAPM, namely 'high-resolution chest" and 'brain perfusion," were not included according to the non-uniform number of studies among the five CT systems. Both protocols were acquired using some CT systems but were limited in the other CT systems.

Conclusion

A review of clinical protocols, CT number accuracy, and low-contrast performance is evaluated annually by a qualified medical physicist. The clinical protocols of the adult head, pediatric head, adult abdomen, and pediatric abdomen examinations are evaluated using the ACR CTAP to obtain the appropriate parameters for each CT scanner. The CNR revealed that the results of all tests are within the acceptable ACR criteria limits.

The evaluation and QC of clinical protocols of CT examinations using the ACR CTAP should be performed annually to ensure the consistency of the CT equipment performance, especially for the low-contrast study.

In summary, the low contrast performance and CNR study according to the ACR standard are particularly important for the annual review of clinical protocols for the improvement of the image quality, diagnosis, and optimization of radiation protection.

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Conflict of interest statement

All authors have completed and submitted the International Committee of Medical Journal Editors Uniform Disclosure Form for Potential Conflicts of Interest. All of the authors declare that they have no conflicts of interest.

Data sharing statement

All data generated or analyzed during the present study are included in the published article. Further details are available for non-commercial purposes from the corresponding author upon reasonable request.

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