Polish Journal of Medical Physics and Engineering
The Journal of Polish Society of Medical Physics
ISSN 1898-0309, doi: 10.2478/pjmpe-2026-0021

September 2026
Vol 32, Issue 3

Scientific Paper

Exploring the effectiveness of CARE Dose 4D and CARE kV Automatic Exposure Control Systems in CT: A Slim and Obese Phantom Study

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(received 12 June 2026; revised 02 August 2026; accepted 01 September 2026)

Abstract

Introduction: Radiology strives to minimise radiation exposure while maintaining diagnostic image quality. AEC systems achieve this by optimising radiation doses across different patients and anatomies. The purpose of our study was to evaluate the performance of AEC using Siemens CARE Dose4D and CARE kV options for both slim and obese adult phantoms. We focused on assessing how different parameter settings affect radiation dose and image quality.

Material and methods: Examinations were performed on a dual-source CT scanner using a slim and obese anthropomorphic phantom and a Catphan phantom. Parameters such as mAs modulation strength, reference kV values, quality reference mAs values, dose optimisation settings and CARE kV option were adjusted. The collected data included mA modulation, $CTDI_{vol}$, effective mAs, quality reference mAs, reference mAs, kV values, and the relative standard deviation of HU values.

Results: The quality reference mAs serves as the baseline target for image quality and is influenced by the CARE kV mode, thereby designating the reference mAs ('off' matches the baseline exactly; 'on' scales with the reference kV; 'semi' scales inversely with the reference kV). The effective mAs represents the final value influenced by all forms of modulation. For the slim phantom, the effective mAs remained lower than the reference mAs, while for the obese phantom, it was higher. The adjusted reference mAs values appear independent of phantom size. mA modulation curves reflect the link between CTD_{Ivol} and AEC. Regardless of the phantom's body type, $CTDI_{vol}$ decreased/increased when dose-saving optimiser levels, quality mAs_{ref}, and kV_{ref} were changed. Higher modulation strength lowers the dose for slim phantoms, but raises it for obese phantoms. Slim phantoms produce a lower relative standard deviation than obese ones.

Conclusions: Radiologists and medical physicists must understand the mechanics of the AEC system in CT scanners. This knowledge is essential for ensuring consistent image quality and minimising patient exposure.

Keywords: Computed tomography, dual-source computed tomography, Automatic Exposure Control System, CARE Dose 4D, CARE kV

Introduction

Enhancing the quality and safety of diagnostic imaging procedures is a key challenge in radiology, especially given the increasing complexity of examinations that benefit patients[1]. The objective is to minimise radiation doses to the lowest levels that are reasonably achievable while still maintaining adequate image quality for clinical use. This can be accomplished through the Automatic Exposure Control (AEC) system, an advanced technology designed to optimise radiation doses

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Authors' contribution: A – Research concept and design, B – Collection and/or assembly of data, C – Data analysis and interpretation, D – Writing the article, E – Critical revision of the article, F – Final approval of the article.

while maintaining consistent image quality across different patients and anatomical regions[2]. It is essential to know that the operation of this system is specific to the manufacturer[3]. In computed tomography, AEC technology has evolved over time, beginning with manual selection of exposure parameters (fixed dose), followed by longitudinal (z-axis) modulation, angular (x-y) modulation, combined „3D/4D" technology, automated kV selection, and modulation utilising organ-based techniques[3,4]. Nowadays, AEC systems adapt to changes in scan and reconstruction parameters; however, this response can vary significantly across vendors and CT scanner types[3]. This variability is a critical consideration for radiologists and medical physicists as they strive for consistent image quality, minimal patient exposure across different CT units.

CARE Dose 4D and CARE kV

Siemens' CARE Dose 4D automatic exposure control system optimises radiation doses during imaging procedures by employing various radiation-reduction techniques. These techniques adjust the tube current based on specific patient characteristics, such as size, shape, and density, while maintaining the target image quality as specified by the user[2,4]. CARE Dose 4D features include the adaptation of milliampere-seconds (mAs) based on topogram (patient body size), and the AEC system cannot be active without a topogram[5]. Additionally, z-modulation (longitudinal modulation in the z-direction) and angular modulation (in both the x- and y-directions) of the tube current occur, allowing for more precise adjustments based on the patient's shape[2]. The tube current is modulated during each rotation of the acquisition, with a half-rotation delay, providing real-time feedback based on the patient's shape[4]. It means the real-time feedback loop uses attenuation data from the previous 180° rotation to instantly calculate the required dose for the next projection. Considering the above, the „4 dimensions" refer to four distinct types of modulation: patient's body size, angular, longitudinal, and real-time. Users can set specific parameters, such as the quality reference mAs (q_mAs_{ref}) and reference kV (kV_{ref}), to define the desired image quality level for a standard-sized patient[6]. Configurable settings, known as modulation strength or adaptation strength, determine how aggressively the system modulates the tube current. The tube current will be adjusted according to body type[4]. For slim bodies or body parts, the current will be set to weak, average, or strongly decreased. In contrast, for obese bodies or body parts, it will be set to weak, average, or strongly increased[7]. Typically, manufacturers configure the adaptation strengths to default to an average decrease for slim body parts (or body) and an average increase for obese parts (or body)[3]. Modulation strength has a global impact on CARE Dose 4D and is applicable across different organs, though it is not specific to any particular protocol[4]. The q_mAs_{ref} is expressed in terms of effective mAs (mAs_{eff}), which is calculated by dividing the actual tube current-time product (mAs) by the spiral pitch value[8]. q_mAs_{ref} is set to correspond to the mAs_{eff} that yields the desired image quality for a standard-sized patient (70-80 kg) and meets the diagnostic requirements[5,7]. The actual attenuation for a given patient is determined from the topogram (scout, planning sequences). Depending on the selected scanning protocols and the patient's body size, the mAs_{eff} value may increase or decrease during acquisition. Additionally, the CARE kV (Automatic Tube Voltage Selection) setting is available; when active, the system selects the optimal kV to maintain a desired image quality[9]. This value is selected from a range defined by the limits configured in the Scan Protocol Assistant and is based on the exam type specified by the dose optimisation slider (dose-saving optimiser) setting, depending on the type of examination. q_mAs_{ref}, kV_{ref}, and the dose optimisation slider settings are specific to a particular scanning protocol (specified in the scan card) and do not affect the overall settings in other protocols.

This study aimed to evaluate the effectiveness of an automated exposure control system that utilises the CARE Dose 4D and CARE kV options developed by Siemens Healthineers (Erlangen, Germany). Existing literature has primarily examined the impact of mAs modulation strength using both standard and pediatric phantoms[2,3,7] and CARE kV mode[10–14]. However, due to the complexity of AEC systems, it is advisable to analyse the characteristics of each system under different imaging conditions[15]. Therefore, our objective was to evaluate the overall performance of the AEC system (CARE Dose 4D and CARE kV) by using a range of user-defined technical parameters and different adult body types in a single study. This approach, in our opinion, improves the thoroughness of AEC system evaluation, yielding both obvious and intriguing results. We focused on assessing the system's effectiveness for both slim and obese adult patients, simulated with phantoms. This involved considering variations in parameter settings, including reference kV values, quality reference mAs values, dose optimisation settings based on the type of examination, and mAs modulation strength. We also evaluated the implications of these variations on imaging by analysing the relative standard deviation of Hounsfield units.

Materials and methods

The study was carried out in the Department of Radiology at a medical university hospital. Examinations were performed using the dual-source computed tomography device, Somatom Force (Siemens Healthineers, 2019), in accordance with the procedure described below. The CT unit's software version is Syngo CT VB20A, running on the Somaris 7 platform. The CT scanner is regularly tested for quality control by qualified on-site medical physicists, in accordance with national legal quality standards.

Data acquisition

Measurements were conducted using both an anthropomorphic phantom and a technical phantom. The phantoms were centrally positioned since accurate patient alignment at the isocenter is essential for precise attenuation calculations in CT scanners[4,16]. The measurements were taken by adjusting the

mAs modulation (adaptation) strength to patient size (separately for adult slim and adult obese patients). This modulation strength was changed for the abdomen (as an organ characteristic). The mAs strength was adjusted according to a five-point modulation scale in the CARE Dose 4D configuration, with the following categories: 'very weak', 'weak', 'average', 'strong', and 'very strong'. Measurements were carried out for variable kV_{ref} and q_mAs_{ref} values, as well as for variable settings of dose optimisation according to the type of examination. If the modulation strength was not changed, the baseline was set according to the clinical practice used at the site, with a 'strong' serving as the reference point for the obese anthropomorphic phantom and a 'very weak' for the slim phantom (e.g., Catphan and slim anthropomorphic phantom). Additional measurements were carried out by adjusting the CARE kV settings for the Catphan phantom. Before each scan, anterior-posterior and lateral topograms were obtained, as they provide better dose-sparing than a single AP topogram alone[5]. The most significant exposure parameters are summarised in **Table 1**.

The study utilised a customised scan protocol specifically developed for non-contrast abdominal imaging. A user-defined protocol was established based on the manufacturer's provided scan protocol (the base protocol), which cannot be altered. The base protocol includes details about the anatomical structures within the expected scan range, along with their corresponding reference attenuation values. It also specifies the default modulation type (x, y, or z, or a combination of both) used by the CT scanner[4]. Even though the CT unit is equipped with two X-ray tubes, the standard abdominal protocol without contrast medium is not a multi-energy protocol and therefore uses only one of the tubes.

Based on the information provided, the parameters set by the user were as follows:

- quality reference mAs (q_mAs_{ref}),
- reference kV (kV_{ref}),
- mAs modulation (adaptation) strength in the CARE Dose 4D, configuration: 'very weak', 'weak', 'average', 'strong', and 'very strong',
- dose optimisation according to the type of examination: non contrast / bone / soft tissue contrast / vascular,
- CARE kV 'on', 'semi', 'off'

and adjusted by CARE Dose 4D and CARE kV:

- effective mAs (mAs_{eff}),
- reference mAs (mAs_{ref}),
- kV.

Phantom

Three phantoms were scanned with different AEC settings within a constant anatomical range. A whole-body anthropomorphic phantom (PBU-60, Kyoto Kagaku, Japan, **Figures 1** and **2**) and the Catphan 600 phantom (The Phantom Laboratory, USA) were used to simulate a patient with an adult slim body shape. This phantom is a life-size replica of a human body (accurately models the size, shape, and internal structure of an adult slim), with an approximate length of 165 cm and a weight of about 50 kg[17]. Its materials and individual organs exhibit attenuation properties that closely resemble those of the human body, yielding similar HU values. This enables the effective simulation of a patient scan. The phantom dimensions measured on the CT image were 19.4 cm in the anterior-posterior (AP) direction and 27 cm in the lateral (LAT) direction.

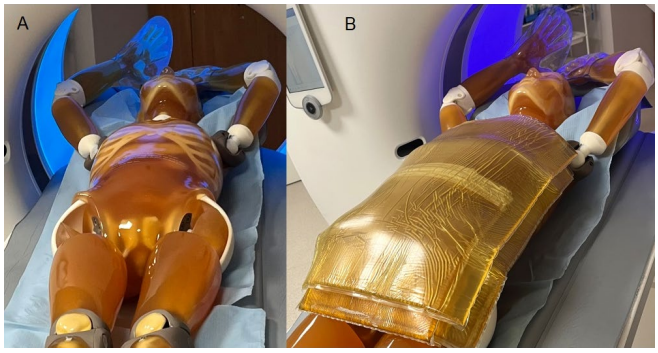


Figure 1. Positioning of the anthropomorphic phantom during CT acquisition: (A) slim body configuration (baseline PBU-60 phantom) and (B) obese body configuration, achieved by applying 6.5 cm of tissue-equivalent bolus material. Both setups feature the arms in an overhead position

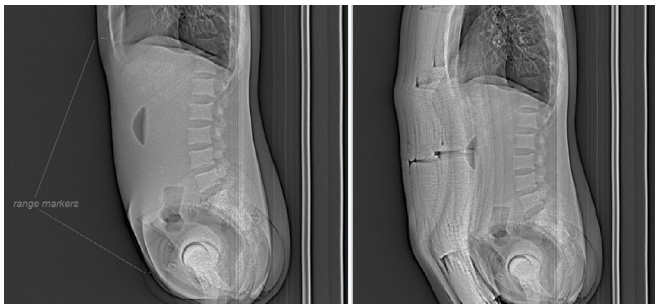


Figure 2. Lateral views of the phantoms used for a slim adult and an obese adult. The fixed transverse-scanning range for both phantoms' examinations is shown in the slim phantom view

To simulate an obese adult human body, additional radiotherapy (Action® Bolx-II) boluses were used (6.5 cm total thickness, as shown in **Figures 1** and **2**). These boluses were used to prompt the scanner to adjust the mAs strength in CARE Dose 4D mode for an obese patient. The system estimates the patient's size from the topogram (scout image) rather than relying on manually entered weight and height on the scanner console. Action® Bolx-II boluses are specifically designed for use as materials in radiation therapy and diagnostic X-ray applications[18]. As the earliest application in clinical settings, the bolus is utilised in megavoltage radiotherapy as a compensatory material to enhance the surface dose when the build-up effect limits dose delivery to the superficial tissue layers[19]. The proprietary elastomer gel (with a physical density of approximately 1.00 g/cm^3) used by Action Products closely mimics the physical characteristics of soft tissue, thereby enabling the accurate simulation of a patient's external body layers[18].

Data analysis

The mean HU and standard deviation (SD) measurements in the whole-body anthropomorphic phantom were performed in the liver, as it is the most homogeneous organ in the scanned volume. **Figure 3** illustrates the placement of the 12 cm^2 circular ROI within the liver for both the slim and obese phantom configurations.

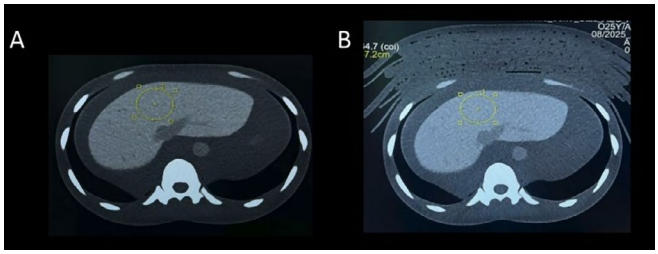


Figure 3. Placement of the Region of Interest (ROI, 12 cm2 area) for CT number measurements within the liver for the slim (A) and obese (B) adult phantoms

Using data from the anthropomorphic phantom, HU and SD values were measured with the AW 4.7 station (GE HealthCare). To minimise potential observer bias, measurements were prepared by a single operator. The true Coefficient of Variation (CV) of X-ray attenuation was utilised to calculate the relative standard deviation ($SD_{relative}$) with the following formula:

$$SD_{relative} = \frac{SD}{HU + 1000} \qquad \textbf{Equation 1}$$

The expanded uncertainty of the HU measurement was estimated at 1.3% (k = 2; confidence level approximately 95%).

The radiation dose information, expressed as the volume CT dose index ($CTDI_{vol}$) and dose-length product (DLP), was extracted from the DICOM Patient Radiation Dose Structured Report (PRDSR) for each CT scan. The reported $CTDI_{vol}$ is a standardised measure of the CT unit's radiation output, normalised to a 32-cm diameter CTDI body phantom. The deviation between the displayed and measured $CTDI_{vol}$ for the abdomen protocol was recorded as 3.85 %. This measurement was based on $CTDI_w$ and corrected by the pitch factor. The expanded uncertainty of the $CTDI_w$ (or rather DLP) measurement was estimated at 2.0% (k = 2; confidence level approximately 95%).

Data analysis was conducted using Microsoft Excel and the Python programming language, and visualisations were created with Matplotlib and NumPy. The results are displayed in various formats, including bar charts, radar charts, scatter plots, and tables. The mA modulation data were obtained using a macro developed in ImageJ 1.54p (National Institute of Health, USA). Tube current modulations based on slice location were performed for four different examination types (dose-saving optimiser levels) as well as for variation in quality mAs_{ref} and kV_{ref} values. Additional tube current modulations for other CARE Dose 4D settings or scout direction can be found in the literature[2,5,7,15].

The research project does not require approval by the Bioethical Committee, as it was a phantom study with no patient data utilised.

Results

The results evaluating the impact of various AEC system settings (modulation strength, quality reference mAs and kV values, dose-saving optimiser levels, and CARE kV) on radiation dose and image quality metrics are summarised below. Some effects are clear, such as those of q_mAs_{ref} and kV_{ref} on dose, while others, like the influence of CARE kV mode and dose optimiser level on mAs in relation to CARE kV mode or body size, are interesting.

The $CTDI_{vol}$ for three phantom types (CTP, slim, obese) across five levels of *modulation strength* (very weak to very strong):
Larger phantoms require higher baseline doses ($CTDI_{vol}$ increases with stronger modulation), and the effect of modulation strength on dose varies by phantom type -higher mA modulation strength decreases $CTDI_{vol}$ for slim phantoms and increases it for obese phantoms (see **Figure 10** in the Appendix).

The $CTDI_{vol}$ for three phantom types (*CTP*, *slim*, *obese*) across three quality reference mAs values (*q_mAs*ref = 100, 147, 200):
$CTDI_{vol}$ rises with both increasing q_mAs_{ref} and larger phantom size, with the *obese* phantom at q_mAs_{ref} = 200 showing the highest dose (see **Figure 10** in the Appendix).

The $CTDI_{vol}$ for three phantom types (CTP, slim, obese) across three reference kV values (kV_{ref} = 90, 120, 130):
$CTDI_{vol}$ rises with higher kV_{ref} and is consistently highest for the obese phantom across all kV_{ref} values (see **Figure 10** in the Appendix).

The $CTDI_{vol}$ for three phantom types (CTP, slim, obese) across four examination types: *non contrast*, *bone*, *soft tissue contrast*, and *vascular (dose-saving optimiser levels)*:
Larger phantoms require higher radiation doses, and the dose varies by examination type, with non-contrast / bone exams typically demanding more dose than vascular exams (see **Figure 10** in the Appendix).

The variations in tube current across different slice locations are illustrated in **Figure 5**. In this instance, mA modulation is significantly affected by three main factors: the type of examination (with the highest mA used for non contrast and bone examinations, moderate mA for soft tissue contrast, and the lowest for vascular), the size of the phantom or patient, and the anatomical region of the slice (the tube current drops significantly as it moves toward the chest).

The $CTDI_{vol}$ for a Catphan phantom under different CARE kV settings and imaging parameters.

1. $CTDI_{vol}$ increases progressively from CARE kV 'on' and kV = 90 to CARE kV 'off' and kV=130, ranging from 1.96 mGy (lowest) to 7.77 mGy (highest) (see **Figure 10** in the Appendix).
   Figure 6 demonstrates that CARE kV modulates mAs (mAs_{ref} and mAs_{eff}).

2. Reference mAs (mAs_{ref})
   - CARE kV 'off': mAs_{ref} exactly matches the q_mAs_{ref} (147).
   - CARE kV On:
     - At a lower reference kV (90), the system drops the mAs_{ref} significantly to 73.
     - At a higher reference kV (130), the system increases the mAs_{ref} to 224.
   - CARE kV Semi:
     - At a lower reference kV (90), the system drastically increases the mAs_{ref} to 365.
     - At a higher reference kV (130), it drops the mAs_{ref} slightly to 120.
3. Effective mAs (mAs_{eff})
   - for kV_{ref} = 90: The 'semi' mode uses the highest tube current (201 mAs) to compensate for the lower kV, while the 'on' mode automatically increases the actual kV to 110 (110 kV is set as CARE kV min value, **Table 1**), allowing the mAs to drop to its lowest point (37 mAs). The 'off' mode sits in the middle at 91 mAs.
   - for kV_{ref} = 130: The trend inverts. The 'on' mode (which drops actual kV to 110) requires a higher actual mAs (134 mAs). The 'semi' mode maintains the 130 kV and uses the lowest actual mAs (79 mAs).

Adjusting the parameters (kV, $mAs_{ref,}$ mAs_{eff}) using CARE dose 4D and CARE kV for *slim* and *obese anthropomorphic phantoms* across different imaging scenarios.

Figures 4 and **5** demonstrate that CARE dose 4D and CARE kV technology dynamically adjust kV and mAs (mAs_{ref}, mAs_{eff}) parameters based on phantom size (slim vs obese) and imaging requirements. **Figures 7** and **8** illustrate tube current modulation as a function of on-slice location, derived from various combinations of quality mAs_{ref} and kV reference values.

1. Obese vs. Slim Phantoms:
   mAs_{eff} for the obese phantom consistently shows higher mAs values than mAs_{eff} for the slim phantom (e.g., on "q_mAs_{ref} = 200" and "kV_{ref} = 130"), reflecting the need for greater radiation to image larger (obese) phantoms. mAs_{eff} for the slim phantom follows a more moderate pattern, with lower values in most regions.
2. Reference vs. Adjusted Parameters:
   - q_mAs_{ref} and kV_{ref} act as baselines. CARE dose 4D and CARE kV - adjusted values (e.g. mAs_{ref}, mAs_{eff}) deviate from these baselines based on phantom type and imaging conditions.
   - The kV values remain stable even when the kV_{ref} is changed.
   - CARE dose 4D tunes up $mAs_{ref,}$ $mAs_{eff,}$ taking into account the user-set q_mAs_{ref}.

Table 1. The exposure parameters utilised in the experiment

Protocol	Abdomen without contrast (Adult)
Scan mode	Spiral
Single Collimation Width (mm)	0.6
Total Collimation Width (mm)	57.6
Quality reference tube voltage (kV)	$120^{(rp)}$ / 90 / 130
Quality reference mAs	$147^{(rp)}$ / 100 / 200
FAST adjust lower limit max. mAs [%]	25
CARE dose 4D	On
CARE kV min / CARE kV max*	110 / 150
CARE kV optimisation criteria	3
CARE kV	$on^{(rp)}$ / semi / off
Reference kV	120
Rotation time (s)	0.5
Spiral Pitch Factor	0.6
Slice thickness (mm)	1.0
Convolution Kernel	Br40d\3
Iterative recon strength	3
Exposure Modulation Type	XYZ_EC
Filter Type	Flat
Modulation strength	very strong / $strong^{(rp_oa)}$ / average/ weak / $very\ weak^{(rp_sa)}$
Organ Characteristic	Abdomen
Dose Optimisation for variable examination type (dose-saving optimiser levels)	$non\ contrast^{(rp)}$ / bone / soft tissue contrast / vascular

$^{(rp)}$ - exposure parameters used for reference exposure (the reference point), $^{(rp_oa)}$- reference modulation strengths for the obese adult, $^{(rp_sa)}$ - reference modulation strengths for the slim adult (Catphan and slim anthropomorphic phantom)
parameter names according to DICOM headers and CT protocol, * - value specified in the Scan Protocol Assistant

   - The mAs_{ref} values remain stable even when the body size is changed. For a slim phantom, the system selects a lower mAs_{eff} value than mAs_{ref}, while for an obese phantom, it is typically the opposite.
3. Imaging Scenarios:
   - Parameters vary significantly by examination type (e.g., 'bone' vs 'soft tissue') and modulation strength (e.g., "very strong" vs. "very weak"), showing how CARE dose 4D and CARE kV tailor settings to optimise image quality for different anatomical and diagnostic needs.

The *SD*relative for the slim and obese anthropomorphic phantom across various AEC conditions:

1. The obese anthropomorphic phantom exhibits greater measurement variability (higher $SD_{relative}$) compared to the slim phantom across most conditions,
2. The maximum $SD_{relative}$ is observed at kV_{ref} = *90* and the minimum $SD_{relative}$ is observed at q_mAs_{ref} = 200 for slim and obese phantoms (**Figure 9**).

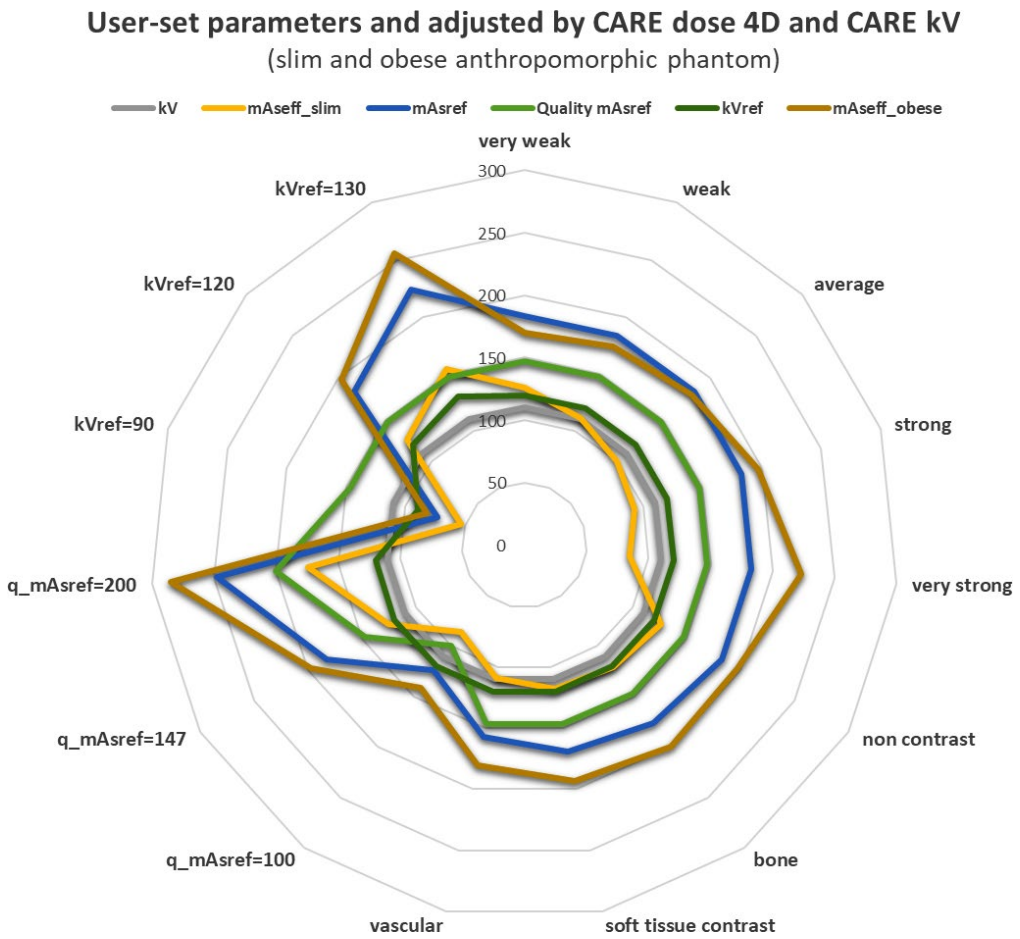


Figure 4. User-defined settings and exposure parameters (mAseff, kV, mAs_{ref}) extracted from the Patient Radiation Dose Structured Report for the slim and obese anthropomorphic phantom. Baseline settings: CARE kV 'on', q_mAs_{ref} = 147, kV_{ref} =120, dose optimisation for variable examination type 'non contrast', level of modulation strength 'very weak' for the slim phantom and 'strong' for the obese phantom, unless otherwise specified.

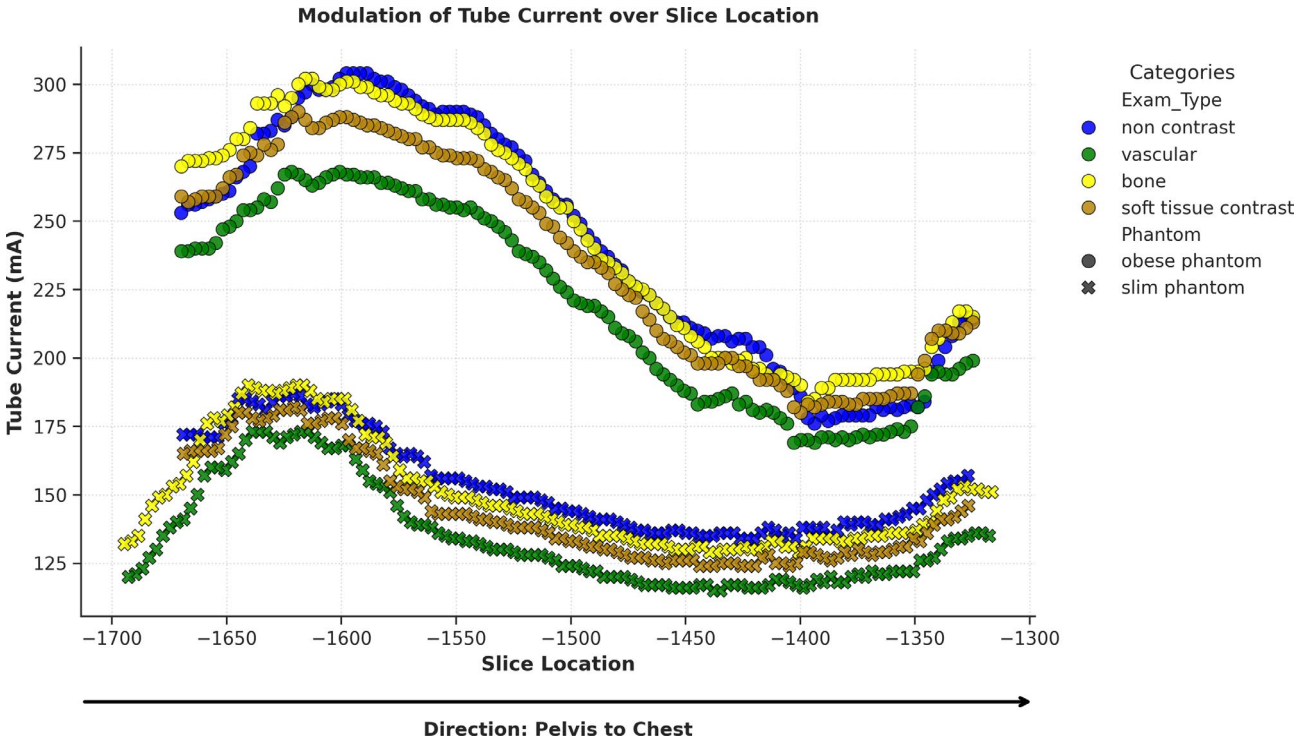


Figure 5. Tube current modulations over slice location across four examination types: non contrast, bone, soft tissue contrast, and vascular

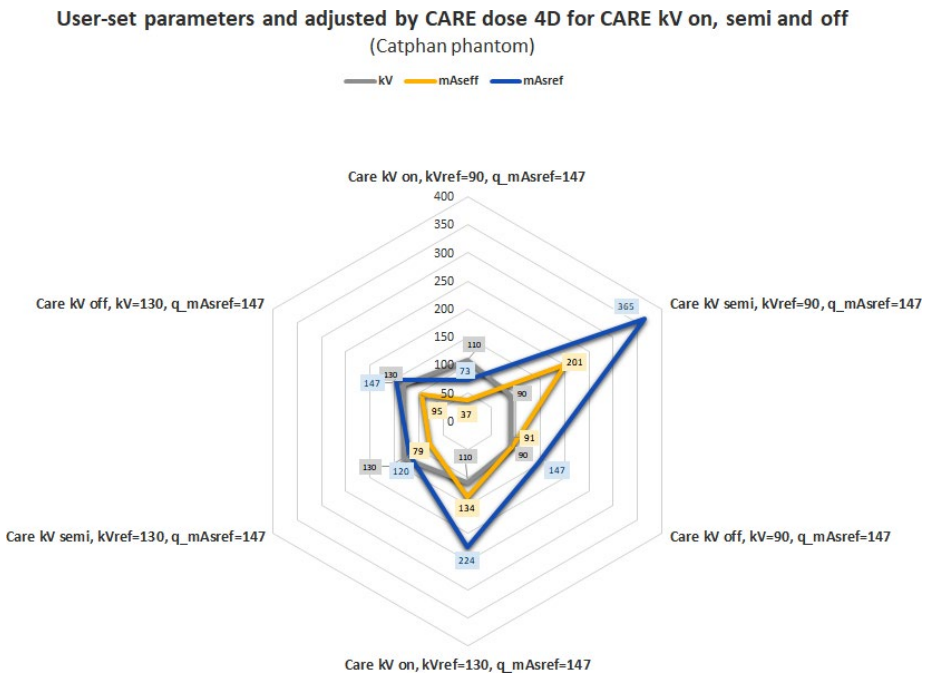


Figure 6. User-defined settings and exposure parameters (mAseff, kV, mAs_{ref}) extracted from the Patient Radiation Dose Structured Report for the Catphan phantom. CARE kV 'on', 'semi' and 'off'. Baseline settings: q_mAs_{ref} = 147, kV_{ref} =90/130, dose optimisation for variable examination type 'non contrast', level of modulation strength 'very weak', unless otherwise specified.

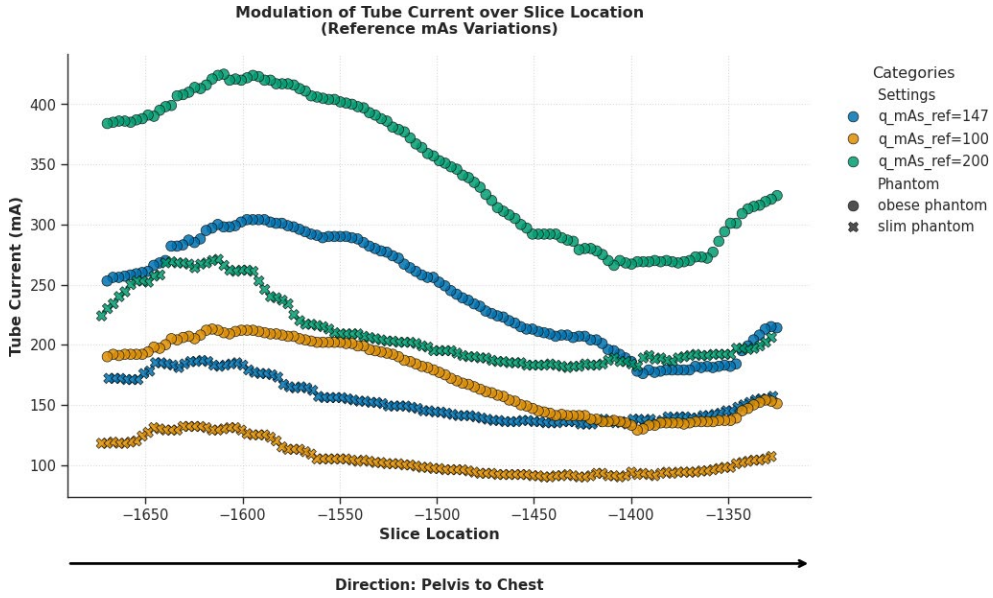


Figure 7. Tube current modulation across slice locations for different quality reference mAs values (q_mAs_{ref}), with the kV reference held constant at 120

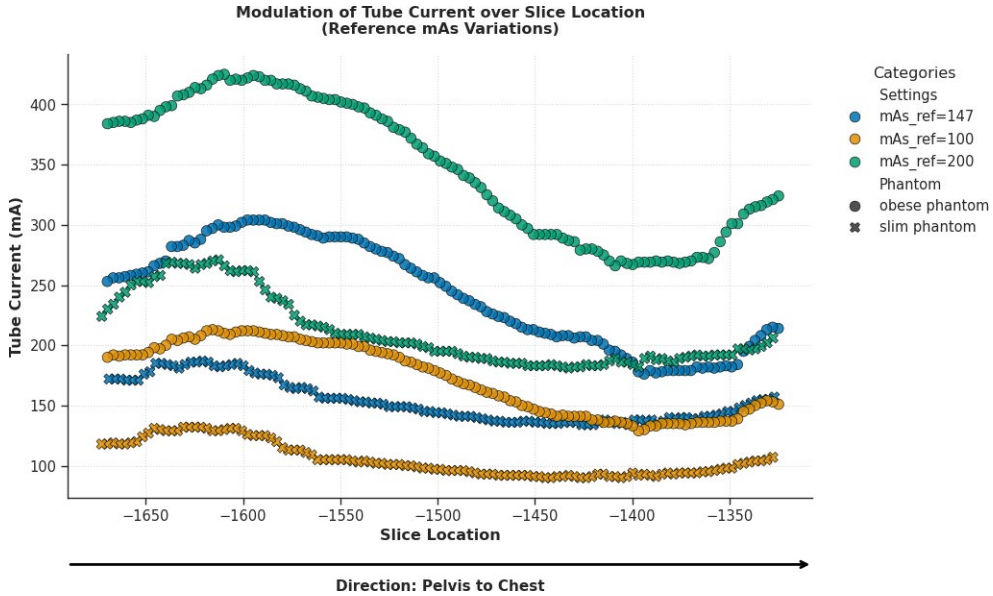


Figure 8. Tube current modulation across slice locations for different reference kV values, with the quality reference mAs held constant at 147

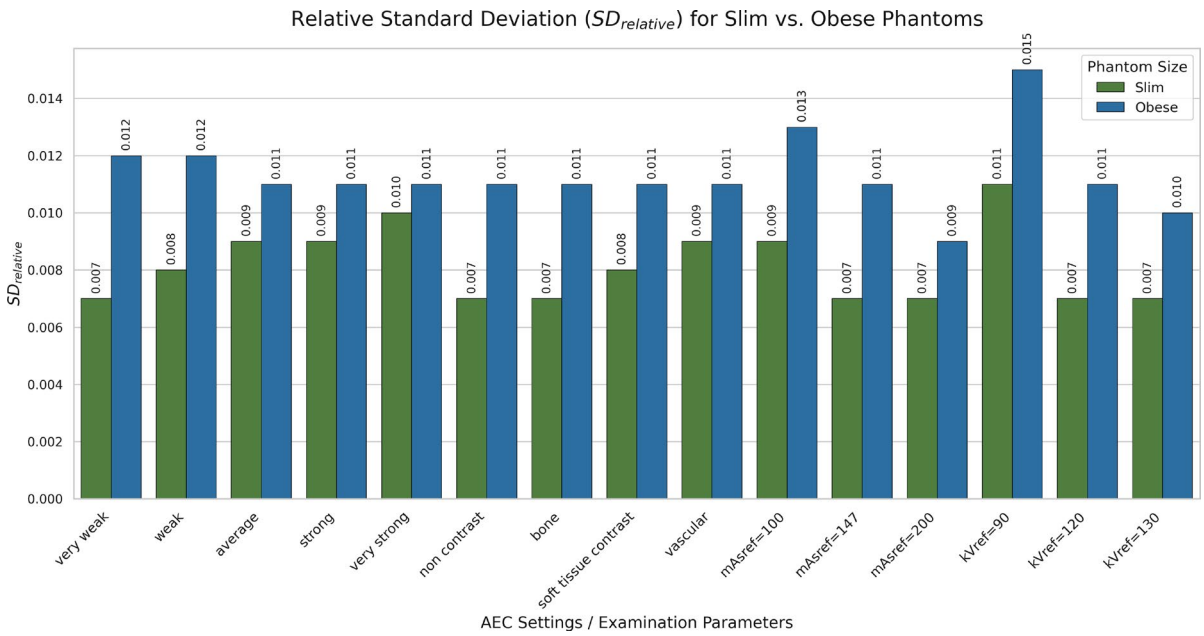


Figure 9. Relative standard deviation SDrelative as a function of body size for slim and obese anthropomorphic phantoms and various AEC settings (the modulation strength, examination type, mAs_{ref} and kV_{ref} values). Baseline parameters: q_mAs_{ref} = 147, kV_{ref} = 120, unless otherwise specified

Discussion

Automatic Exposure Control in computed tomography optimises radiation doses while ensuring consistent image quality across different patients and anatomical regions. In Siemens CT scanners, the AEC functionality is implemented through two features: CARE kV and CARE Dose 4D. These automated, radiation-sparing techniques are fully integrated into the clinical workflow. While CARE Dose 4D adjusts the tube current in real-time, CARE kV optimises the tube voltage. Additionally, various CARE kV modes also influence the tube current. During acquisition, the tube current (and thus the effective mAs) is automatically modulated to account for variations in patient size, shape and tissue density. This adjustment ensures that the image quality remains consistent with the user-defined quality reference mAs level for a standard-sized patient, while still being suitable for both slim and obese patients.

The mAs modulation (adaptation) strength and dose-saving optimiser levels

To control the intensity of the tube current adaptation relative to the patient's body type, the modulation strength parameter is applied. It is critical to recognise that modifying the adaptation strength has a global effect: all protocols that share the same organ characteristics will be updated simultaneously[7]. Our findings confirm the previously established relationship in the literature: a divergent response based on phantom size. Specifically, for the slim phantom, $CTDI_{vol}$ decreases with increasing modulation strength, whereas for the obese phantom, $CTDI_{vol}$ increases with higher modulation settings. Practically, this implies that, if images of slim patients exhibit excessive noise, a CARE Dose 4D curve with lower adaptation intensity (e.g., 'weak' or 'average' decrease) should be selected. On the other hand, if the images of obese patients exhibit high noise levels, a higher-intensity curve (e.g., 'strong' or 'very strong' increase) is required to optimise image quality[6]. The relationship between $CTDI_{vol}$ and different mAs adaptation strengths in our cases is clearly demonstrated by the mAs modulation curves for slim patients reported in the literature[7]. We expect that this relationship would be similar for obese patients as well. Therefore, we decided not to create a separate chart for that scenario and instead presented the relationship using the $CTDI_{vol}$ chart (**Figure 10**).

$CTDI_{vol}$ decreased as dose optimisation varied across examination types: 'non-contrast', 'bone', 'soft tissue contrast', and 'vascular' (see **Figure 10**). This reduction was independent of the phantom's body type, although the difference in dose between ‚non-contrast' and ‚bone' settings was negligible for the obese phantom. The relationship between $CTDI_{vol}$ and different examination types is evident in the modulation curves. The hierarchy of tube current requirements by exam type is consistent for both phantoms. When examining the mA modulation curves for both phantoms, a similar wave-like modulation pattern is displayed as the scan moves from the pelvis to the upper abdomen and chest (see **Figure 2** for a comparison of the scan ranges).

The quality reference mAs, reference mAs and effective mAs:

In the DICOM Patient Radiation Dose Structured Report, the effective mAs and reference mAs are documented alongside $CTDI_{vol}$, DLP, and kV. However, it's important to note that the reported reference mAs did not match the manually configured quality reference mAs value in the scan protocol when CARE kV is set to either 'on' or 'semi' mode. The quality reference mAs serves as the baseline target for image quality specified by the protocol before any modulation-related adjustments are made. Across all experimental cases involving the slim phantom, the effective mAs was consistently lower than the constant quality reference mAs (see **Table 2** and **Fig-**

ure 4). Conversely, for the obese phantom, the reference mAs was significantly higher than the constant quality reference mAs value defined in the settings. The only exception occurred during measurements with variable reference kV (kV_{ref}) values for both phantoms. In these instances, higher effective mAs values were observed relative to the quality reference mAs at elevated kV_{ref} settings (**Table 2**).

Moreover, our experimental results revealed that the reported reference mAs was higher than the user-defined quality reference mAs in nearly all instances. The only exception occurred during measurement with reference kV of 90 and CARE kV enabled. The quality reference mAs value indicates the image quality for a standard patient (70-80 kg)[6] with an abdominal thickness of approximately 33.9 cm[5]. In this study, the slim anthropomorphic phantom (approximately 50 kg) measured 19.4 cm (AP) and 27 cm (LAT). The obese phantom, modified with a 6.5 cm bolus, had a total AP thickness of 26 cm, while the lateral dimension remained constant because the bolus was applied only anteriorly. Notably, the adjusted by system reference mAs values (unlike effective mAs) were independent of body size, they remained consistent for both slim and obese phantoms when identical protocol parameters were applied (see **Table 2**). This may indicate that the reference mAs reported in the DICOM Patient Radiation Dose Structured Report is a pre-calculated parameter rather than a real-time response to the patient's scanned volume (refer to the CARE kV mode discussion below).

As expected, $CTDI_{vol}$ increased with higher-quality reference mAs and reference kV settings, a trend observed consistently across both slim and obese phantoms (**Figure 10**). Specifically, doubling the quality reference mAs from 100 to 200 resulted in a $CTDI_{vol}$ increase of 100% or more. Even more pronounced was the impact of tube voltage, increasing the kV_{ref} from 90 to 130 led to a rise in $CTDI_{vol}$ exceeding 200%. The relationship between $CTDI_{vol}$ and various reference values is clearly reflected in the ratios of the modulation curves (as with the relationship between $CTDI_{vol}$ and different examination types). As both the reference values (including q_mAs_{ref} and kV_{ref}) and the phantom thickness increase, the current values selected by the system also rise (as shown in **Figures 7** and **8**). Both phantoms exhibit the same modulation pattern, which illustrates the transition from the denser pelvic region to the less dense areas in the upper abdomen and chest (see **Figure 2** for a comparison of the scan ranges). Furthermore, the modulation curves for lower reference values (either kV_{ref} or q_mAs_{ref}) appear flatter than those for higher reference values. For all curves, as the scan progresses deeper into the chest region, the tube current increases slightly again.

CARE kV (Automatic Tube Voltage Selection)

For diagnostic CT, using various kV values is crucial to minimise patient radiation exposure and enhance contrast visibility[20]. Many CT scanners now include automatic tube potential (kV) selection tools that determine the optimal kV based on patient size and clinical needs, enhancing radiation dose efficiency[10,12–14]. Analysis of $CTDI_{vol}$ values across different CARE kV (Automatic Tube Voltage Selection) configurations for non-contrast examinations (see **Table 2**, **Figure 10**) studies revealed distinct dose hierarchies depending on the reference settings. When the kV_{ref} (or fixed kV) was set to 90, the radiation dose followed an increasing order of: CARE kV 'on'< 'off'< 'semi'. It is important to note that the kV reference parameter is active only (and thus can be manually inputted) in the 'semi' and 'on' modes when manual kV selection is disabled. In our protocol, the CARE kV limits were set to 110-150 kV in the Scan Protocol Assistant (see **Table 1**). When the kV_{ref} (in 'on' and 'semi' mode) or fixed kV (in 'off' mode) was set to 130, the radiation dose hierarchy shifted to: CARE kV 'semi' < 'on' < 'off'. In the CARE kV 'on' mode, the system proposes an optimised kV and mAs combination based on the patient's topogram and reference settings (kV_{ref} and q_mAs_{ref})[9]. In this study, the system selected the minimum allowed kV value from the CARE kV settings (see **Table 1**) and calculated the significantly lower effective mAs for kV_{ref} = 90, and lower for kV_{ref} = 130, than the quality reference mAs defined by the user. Despite a fixed q_mAs_{ref} of 147, the system derived lower or higher reference mAs values for kV_{ref} settings of 90 and 130, respectively, once CARE kV was activated ('on' mode). In the 'semi' mode, the user-specified kV_{ref} setting is utilised, while adjusting the milliampere-second product based on the user-specified q_mAs_{ref} and topogram[9]. In this mode, even though the q_mAs_{ref} was fixed, the highest mAs_{ref} and mAs_{eff} values recorded across different CARE kV modes occurred at a kV_{ref} of 90. In contrast, when the kV_{ref} was set to 130, the mAs_{ref} and mAs_{eff} values were the lowest observed during the same experiment. When CARE kV is 'off', the scan proceeds with a fixed voltage, bypassing kV optimisation[9]. In our experiment, the effective mAs for the lowest and highest kV settings, in CARE kV is 'off", mode were quite similar to each other, and the reference mAs values were equal to the user set q_mAs_{ref}. These findings confirm that the CARE kV modes influence not only kV but also reference and thus effective mAs, and that the quality reference mAs is affected by the CARE kV 'on' or 'semi' mode.

Image quality - relative standard deviation $SD_{relative}$

Defining appropriate image quality standards for CT examinations remains a primary objective in radiological protection. The EuroSafe Imaging Working Groups (2025-2026) are currently developing strategies to establish organ-specific image quality guidelines tailored to clinical tasks. To evaluate the impact of the AEC setting on image quality in our study, we utilised the relative standard deviation $SD_{relative}$ as a metric for noise performance (**Figure 9**). Our results showed that the slim anthropomorphic phantom consistently exhibited lower $SD_{relative}$ values compared to the obese phantom. A larger patient volume leads to greater X-ray attenuation, resulting in fewer X-ray quanta reaching the detector and consequently higher image noise. This negative effect can be mitigated by adjusting the radiation dose based on the patient's body size. As detailed earlier, CARE Dose 4D automatically adjusts the tube current during the imaging process. Although the $CTDI_{vol}$ values were highest for the obese phantom, the relative standard deviation values for

that phantom were also the highest. This suggests that the dose compensation provided by the AEC system does not fully offset the increased noise associated with larger body mass, resulting in a residual degradation in the signal-to-noise ratio.

Limitations of the study

While this study provides significant insights into AEC behaviour, several limitations should be acknowledged. First, the research did not investigate the combined influence of different minimum and maximum CARE kV settings configured in the Scan Protocol Assistant, alongside the "Dose Optimisation" slider, across various examination types. Measurements in the CARE kV range should include additional reference kV values, as our experiment currently utilises only three.

Furthermore, while our findings are applicable to the Catphan phantom and the specific slim and obese anthropomorphic phantoms used (focused on abdominal organ characteristics), results may vary in clinical practice when applied to patients with diverse anatomical complexities. Using a 6.5 cm anterior bolus to simulate obesity is an oversimplification that does not accurately represent the realistic body composition, fat distribution, and attenuation patterns typically seen in obese patients. This method may distort the AEC response, particularly impacting angular modulation in the x-y plane by overrepresenting attenuation from the anterior-posterior direction while underestimating lateral contributions in the z-plane. Consequently, the modulation patterns observed may not accurately reflect those in actual obese patients. Nevertheless, as discussed in the materials and methods section, we used boluses to prompt the scanner to adjust the mAs in CARE Dose 4D mode for an obese patient.

Future research should repeat these measurements using pediatric phantoms to evaluate their implications for pediatric protocols. Finally, as our analysis was centred on the abdominal protocol, further studies are required to assess other organ characteristics and anatomical regions to ensure broader applicability across the full spectrum of clinical CT imaging.

Conclusions

We comprehensively evaluated the AEC system (CARE Dose 4D and CARE kV) across various technical parameters and adult body types, yielding both expected and intriguing findings.

CARE kV and CARE Dose 4D affects the system-derived reference mAs values, even when the user has set a fixed quality reference mAs. In the DICOM Patient Radiation Dose Structured Report, the reported reference (system-derived / adjusted) mAs does not match the manually configured quality reference mAs value in the scan protocol, when CARE kV is 'on' or 'semi'. The quality reference mAs is the protocol's baseline image quality target before modulation and is influenced by the CARE kV mode, which designates the adjusted reference mAs value (system-derived, reported in P-RDSR). The effect of the CARE kV mode on the quality reference mAs is as follows: When the mode is 'off,' the adjusted reference mAs matches the baseline exactly (q_mAs_{ref}). When it is 'on,' the adjusted reference mAs scales with the reference kV. In 'semi' mode, the adjusted reference mAs appears to scale inversely to the reference kV. The effective mAs is the final value, influenced by all forms of modulation. The adjusted reference mAs values (unlike effective mAs) appear to be independent of body size; they remained consistent for both slim and obese phantoms when identical protocol parameters were applied. We observed that the effective mAs was consistently lower than the reference mAs for the slim phantom, and an opposite trend for the obese phantom.

Furthermore, the settings of the "Dose Optimisation" slider were shown to significantly influence the $CTDI_{vol}$ across all body types. Our findings confirm the literature's evidence of a varied mAs modulation strength response depending on phantom size. In the slim phantom, $CTDI_{vol}$ decreased as the modulation strength increased, whereas the opposite trend was observed in the obese phantom. For a low kV reference or kV value, the radiation dose followed this order: CARE kV 'on' < 'off' < 'semi'. For higher kV reference values, the hierarchy of radiation dose shifted to: CARE kV 'semi' < 'on' < 'off'. The relationship between $CTDI_{vol}$ and different AEC settings is evident in the mA modulation curves.

The Siemens CARE Dose 4D system exhibits a divergent response to patient habitus: while it prioritises dose reduction in slim patients, it significantly increases the radiation output ($CTDI_{vol}$) in obese patients to maintain an acceptable signal-to-noise ratio. Dose compensation provided by the AEC system does not fully offset the increased noise associated with larger body mass, resulting in a residual degradation of the signal-to-noise ratio.

Radiologists and medical physicists must understand the mechanics of the AEC system in CT scanners. This knowledge is essential for ensuring consistent image quality and minimising patient exposure. When preparing a scan protocol, they must carefully select the appropriate options to strike an effective balance between dose efficiency and diagnostic needs.

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

Funding

The research was funded by the Medical University of Silesia in Katowice, supported by the Medical Research Agency, Poland (Grant 2023/ABM/01/00031).

Appendix

Figure 10 and **Table 2** can be found in the appendix.

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Appendix

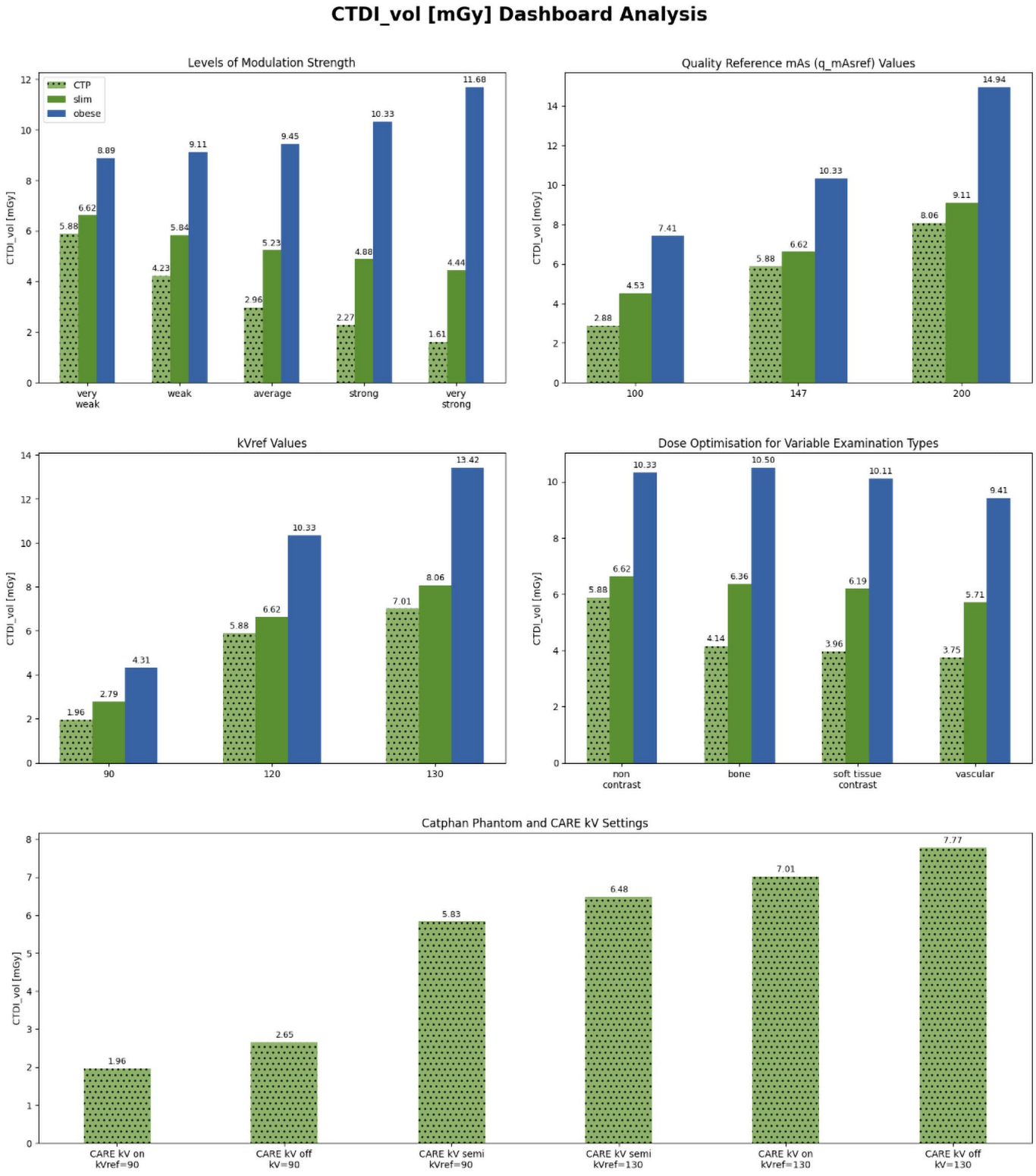


Figure 10. CTDIvol for various phantoms (CTP - Catphan 600 / slim, obese - anthropomorphic phantom) and modulation strength (top left), other parameters: adjusted mAs_{ref} = 183 (setting in CT protocol: q_mAs_{ref} = 147, kV_{ref} = 120), dose optimisation for variable examination type 'non contrast', CARE kV 'on'; quality mAs_{ref} (q_mAs_{ref}) values (top right); other parameters: kV_{ref} = 120, levels of modulation strength 'very weak' (CTP and slim), 'strong' (obese), dose optimisation for variable examination type 'non contrast', CARE kV 'on'; kV_{ref} values (middle left); other parameters: q_mAs_{ref} = 147, dose optimisation for variable examination type 'non contrast', CARE kV 'on', levels of modulation strength 'very weak' (CTP and slim), 'strong' (obese); dose optimisation level for variable examination types (middle right), other parameters: q_mAs_{ref} = 147, kV_{ref} = 120, levels of modulation strength 'very weak' (CTP and slim), 'strong' (obese), CARE kV 'on'; CARE kV settings (bottom), kV_{ref} values 90 and 130, other parameters: q_mAs_{ref} = 147, dose optimisation for variable examination type 'non contrast', level of modulation strength 'very weak', CARE kV 'on', 'semi', 'off'.

Table 2. User-set parameters from the Patient Radiation Dose Structured Report for the slim and obese anthropomorphic phantom. CARE kV 'on', q_mAsref = 147 and kVref =120, dose optimisation for variable examination type: 'non contrast', levels of modulation strength 'very weak' (slim phantom), 'strong' (obese phantom), unless otherwise specified.

Parameter changed	Option	P-RDSR			User-set parameters			
		DLP [mGycm] slim / obese phantom	kV	mAs_{eff} slim / obese phantom	mAs_{ref}	q_mAs_{ref}	kV_{ref}	Dose Optimisation for variable examination type
Modulation strength	'very weak'	243.1 / 328.1	110	126 / 170	183	147	120	non contrast
	'weak'	215.5 / 335.7		111 / 174				
	'average'	193.2 / 349.9		100 / 180				
	'strong'	180.0 / 380.1		93 / 197				
	'very strong'	164.2 / 431.0		85 / 223				
Dose optimisation level for variable examination types	'non contrast'	243.1 / 380.1		126 / 197				non contrast
	'bone'	96.1 / 388.6		79 / 200	176			bone
	'soft tissue contrast'	91.8 / 374.1		75 / 193	169			soft tissue contrast
	'vascular'	86.2 / 348.3		71 / 180	157			vascular
q_mAs_{ref}	mAs_{ref} = 100	166.6 / 274.1		86 / 141	124	100	120	non contrast
	mAs_{ref} = 147	243.1 / 380.1		126 / 197	183	147		
	mAs_{ref} = 200	334.7 / 553.1		174 / 285	248	200		
kV_{ref}	kV_{ref} = 90	102.7 / 159.4		53 / 82	73	147	90	
	kV_{ref} = 120	243.1 / 380.1		126 / 197	183		120	
	kV_{ref} = 130	296.7 / 496.0		154 / 256	224		130	
CARE kV	kV_{ref} = 90_CARE kV on	46.7	110	37	73		90	non contrast
	kV_{ref} = 90_CARE kV semi	137.7	90	201	365			
	kV = 90_CARE kV off	62.6		91	147		---	
	kV_{ref} = 130_CARE kV on	165.0	110	134	224		130	
	kV_{ref} = 130_CARE kV semi	152.9	130	79	120			
	kV = 130_CARE kV off	183.5		95	147		---	

P-RDSR - Patient Radiation Dose Structured Report
mAs_{eff} – effective mAs / mAs_{ref} – reference mAs / q_mAs_{ref} - quality reference mAs