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Contrast-specific conversion factor for accurate radiation dose estimation in contrast-enhanced abdominal computed tomography

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ABSTRACT

Objectives: The objective of the study is to determine the contrast-specific conversion factor (cCF) based on the dose differences between non-enhanced computed tomography (NECT) and contrast-enhanced CT (CECT) in abdominal imaging, with the aim of improving the accuracy of radiation dose estimation in contrast-enhanced examinations.

Material and Methods: The study included 33 adult patients who underwent both NECT and CECT. CECT image acquisition commenced 80 s after the start of iodinated contrast medium injection. A Monte Carlo simulation tool was used to estimate the radiation dose delivered to each patient during NECT and CECT. Organ doses for the liver, spleen, and both kidneys were measured using 120-kVp images. The cCF was calculated as the ratio of the organ dose in CECT to that in NECT. The cCF values are dependent on the scan protocol-, CT vendor-, and X-ray photon energy.

Results: The mean organ doses during NECT were 10.45 mGy for the liver, 11.19 mGy for the spleen, and 11.47 mGy for both kidneys. During CECT, these values increased to 15.83 mGy, 17.56 mGy, and 20.75 mGy, respectively. The mean cCFs of CECT relative to NECT were 1.52 for the liver, 1.83 for the spleen, and 1.87 for both kidneys.

Conclusion: Applying the cCF to NECT-based dose estimates enables more accurate assessment of radiation exposure in CECT examinations.

Keywords: Contrast-enhanced computed tomography, Contrast-specific conversion factor, Non-enhanced computed tomography, Radiation dose estimation

INTRODUCTION

Computed tomography (CT) is widely used across a broad range of clinical applications. However, the increasing use of CT has raised growing concerns about the stochastic risks associated with radiation-induced malignancies.^[1,2] A recent study reported that approximately 5% of annual cancer cases in the United States – equivalent to about 100,000 cases – may be attributable to CT use.^[3] Another large-scale meta-analysis involving 111.6 million adult participants across three continents (Asia, Europe, and North America) demonstrated a disproportionately high increase in cancer risk associated with CT scans in adults.^[4] Furthermore, the observed cancer risk was

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positively correlated with both the radiation dose and the anatomical region scanned.^[5,6]

To accurately assess these risks, it is essential to provide more precise radiation dose estimates and to optimize dose protocols. Conventionally, the risk of radiation-induced cancer from CT is assessed using the effective dose, which is calculated by multiplying the dose-length product or CT dose index (CTDI) by standardized conversion factors derived from phantom-based Monte Carlo simulations.^[7-9] Size-specific dose estimates (SSDE), which account for patient body size, are also widely used as indicators of radiation dose.^[10,11] However, these conventional metrics do not consider the increased radiation dose associated with the use of contrast media. In contrast-enhanced CT (CECT), the radiation dose is typically higher than in NECT, primarily due to the increased photoelectric effect caused by the contrast agent.^[12-14] As a result, the administration of contrast media may lead to a greater radiation burden than previously estimated. Therefore, to improve the accuracy of radiation dose estimation in CECT, the NECT dose should be multiplied by a contrast-specific conversion factor (cCF).

The aim of this study was to determine the cCF based on the dose differences between NECT and CECT in abdominal imaging, to improve the accuracy of radiation dose assessment in contrast-enhanced examinations.

MATERIAL AND METHODS

Patients

This retrospective study was approved by the local institutional review board, which waived the requirement for informed consent.

The study cohort comprised 33 adult patients who underwent both NECT and CECT of the abdomen between August and September 2024 for various clinical indications. The cohort included 24 men and 9 women, with a mean age of 71 years (range, 40–92 years) and a mean body weight of 65.1 kg (range, 41.0–101.2 kg).

Helical scan parameters and image reconstruction

A helical scan was acquired using a third-generation 320-row multidetector CT (Aquilion ONE GENESIS; Canon Medical Systems, Tokyo, Japan). The scanner parameters were as follows: tube voltage, 120 kVp; detector configuration, 80 × 0.5 mm; slice thickness, 5.0 mm; slice interval, 5.0 mm; gantry rotation time, 05 s; pitch factor, 0.8; display field of view, 320 × 320 mm to 400 × 400 mm (adjusted to the patient's body size); and matrix, 512 × 512. Regarding the CECT, iodinated contrast medium (CM) was administered at a dose of 600 mgI/kg over 30.0 s, followed by 30 mL of saline

solution. Image acquisition for CECT was started at 80 s after the start of iodinated CM injection.

All images were reconstructed with deep learning reconstruction (advanced intelligent clear-IQ engine body sharp) algorithms with noise strength at a mild level.

CT number for 120-kVp images

The CT numbers for the liver of each patient were measured using 120-kVp images acquired on NECT and CECT. The standard deviation of the image pixel values was calculated using the NECT and CECT images. The region of interest (ROI) was positioned in the healthy parenchyma at the middle level to avoid vessels in the right lobes. ROI identical in terms of size, shape, and anatomical position were employed for NECT and the corresponding CECT images of the same patient.

Organ dose estimation

A Monte Carlo simulation tool (ImpactMC; VAMP GmbH, Erlangen, Germany) was used to estimate the radiation dose delivered to each patient during NECT and CECT examinations. For the X-ray spectrum data, shaped filters were incorporated based on actual measurements of the aluminum half-value layer and off-center ratio, as described previously.^[15,16] Individual organ doses for the liver, spleen, and both kidneys were obtained from the Monte Carlo simulation results. For NECT, the simulation used air, water, and bone materials. In the case of CECT, the simulation included iodinated CM, taking into account the relationship between iodine enhancement and iodine volume, as the iodine volume increases with higher iodine enhancement. In the CECT, the materials used for Monte Carlo simulation were classified as water-like materials for values <50 HU and as iodine material for values ≥50 HU, based on the mean attenuation of the liver on NECT. The volume fractions of water and iodine at 120 kVp were determined for each 10-HU increment in iodine enhancement and incorporated into the simulation. When the iodine enhancement of the liver was 80 HU, iodine uptake corresponding to 30 HU was included in the simulation. The primary focus of this study was to quantify the cCF, defined as the ratio of each organ dose in CECT to that in NECT. To ensure comparability, the volume CTDI used for NECT was matched to that of CECT in the Monte Carlo simulations, regardless of actual NECT scanning differences. The organ doses for the liver, spleen, and both kidneys of each patient were measured using 120-kVp images. The measurements of organ dose for the liver were applied in the upper and lower positions of the right lobes, whereas those of both kidneys were applied at the level of the renal hilum. ROIs identical in terms of size, shape, and anatomical position were employed for NECT and the

corresponding CECT images of the same patient. Finally, the cCF was calculated as the ratio of the radiation dose in CECT to that in NECT.

RESULTS

CT number and standard deviation

Table 1 shows the mean CT number and image noise for the 120-kV images acquired using NECT and CECT of the liver portions. The mean CT numbers and standard deviation for the liver were 51.7 ± 7.99 HU for NECT and 105.5 ± 12.93 HU for CECT.

Organ dose for NECT and CECT

Figure 1 shows the NECT and CECT images along with both dose maps. Figure 2 represents the organ doses for the liver,

spleen, and both kidneys on NECT [Figure 2a] and CECT [Figure 2b]. The mean organ doses and 95% confidence interval (CI) for the upper and lower portions of the right liver were 10.28 ± 3.681 mGy (95% CI: 8.98 to 11.59) and 10.62 ± 3.558 mGy (95% CI: 9.36 to 11.88), respectively, on NECT. In contrast, the organ doses and 95% CI on CECT were 16.31 ± 5.759 mGy (95% CI: 14.27 to 18.36) and 15.35 ± 5.104 mGy (95% CI: 13.54 to 17.16) for the upper and lower portions of the right liver, respectively. The organ dose and 95% CI for the spleen were 11.19 ± 3.920 mGy (95% CI: 9.80 to 12.58) on NECT and 17.56 ± 5.751 mGy (95% CI: 15.52 to 19.96) on CECT. The organ doses and 95% CI for the right and left kidneys were 11.39 ± 3.824 mGy (95% CI: 10.04 to 12.75) and 11.55 ± 3.964 mGy (95% CI: 10.14 to 12.95), respectively, on NECT. On CECT, the organ doses were 20.76 ± 6.864 mGy (95% CI: 18.33, 23.20) for the right kidney and 20.74 ± 7.452 mGy (95% CI: 18.10, 23.38) for the left kidney.

cCF between NECT and CECT

Figure 3 presents the cCF values for the liver, spleen, and kidneys on CECT in comparison to NECT. The mean cCF for CECT relative to NECT was 1.59 and 1.45 for the upper and lower portions of the right liver, respectively; 1.83 for the spleen; and 1.83 and 1.90 for the right and left kidneys, respectively.

	Mean CT number	Image noise
Non-enhanced CT	51.7	7.99
Contrast-enhanced CT	105.5	12.93

CT: Computed tomography

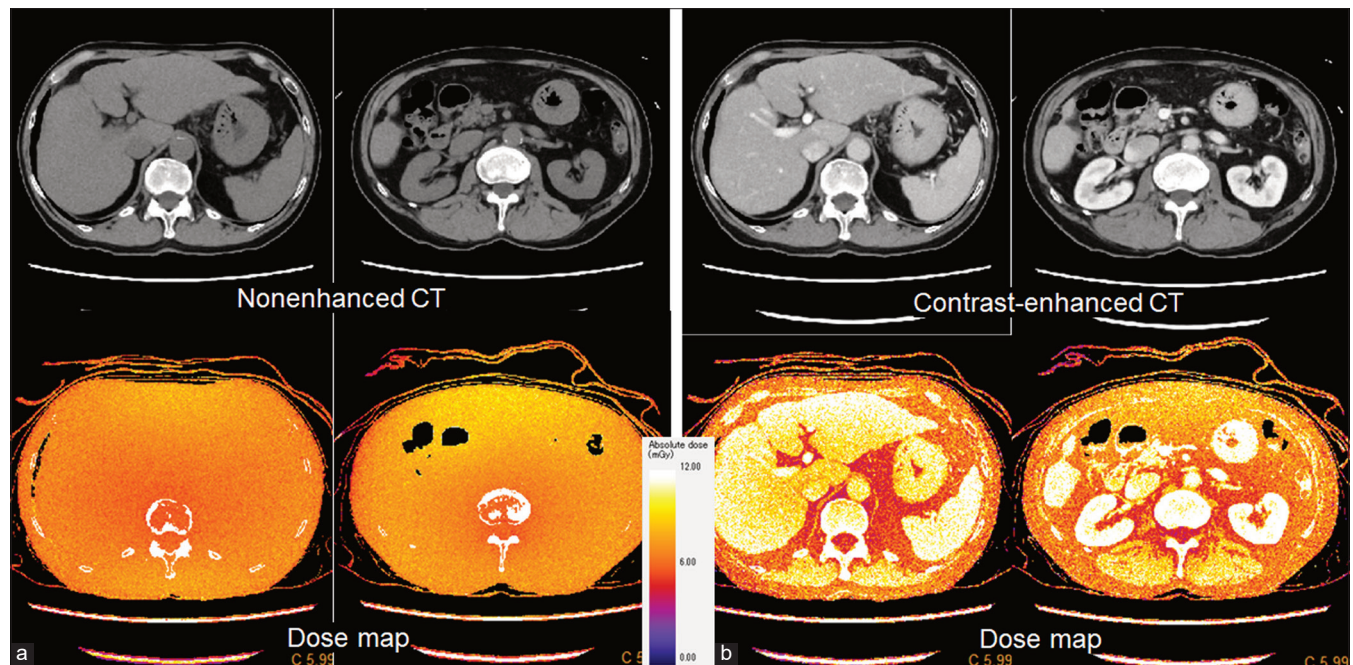


Figure 1: A 74-year-old man. The top row presents nonenhanced (a) and contrast-enhanced (b) CT images at the levels of the liver and kidneys. The bottom row displays the corresponding radiation dose maps at the same anatomical levels. The dose maps indicate higher radiation doses with increasing whiteness. (a) In NECT, bone exhibited the highest dose, whereas the liver and kidneys showed comparable dose levels. (b) In contrast, in CECT, the doses in the kidneys were increased compared with that in the liver, reflecting higher contrast enhancement in the kidneys. In addition, in the liver, higher doses were observed near the surface, with a gradual decrease toward internal regions, as indicated by the color gradient.

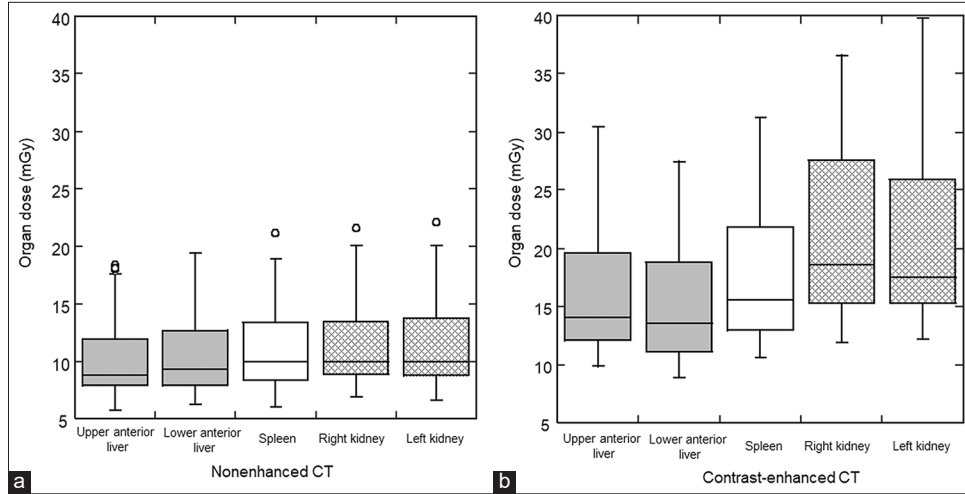


Figure 2: Organ doses for the liver, spleen, and both kidneys on (a) nonenhanced CT and (b) contrast-enhanced CT. (a) In NECT, the radiation doses in the liver, spleen, and kidneys showed no substantial differences among the organs and were nearly comparable. (b) In CECT, reflecting organ-specific contrast enhancement, both kidneys exhibited the highest dose, followed by the spleen and the liver.

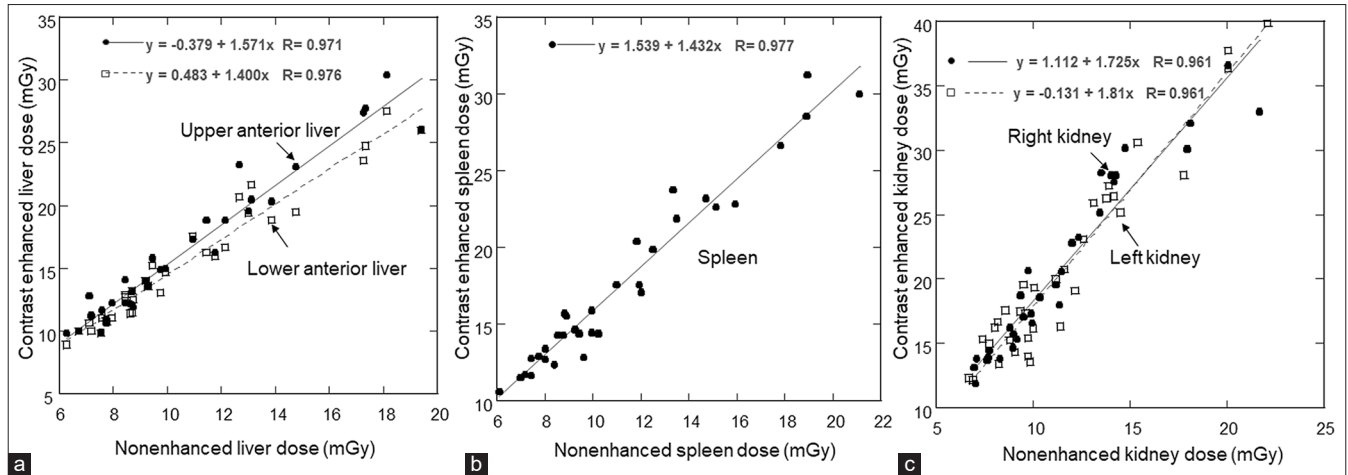


Figure 3: Contrast-specific conversion factor for the liver (a), spleen (b), and kidneys (c) on contrast-enhanced CT in comparison to nonenhanced CT. The graph shows organ doses in NECT on the horizontal axis and those in CECT on the vertical axis. Two regression lines are shown for the liver (upper and lower anterior liver regions) and for the kidneys (right and left kidneys). As the NECT dose increased, the CECT dose also increased, with high correlation coefficients ranging from 0.96 to 0.98. The slope of each regression line represents the cCF, with the kidneys showing the highest values. The slopes (cCFs) were identical for both kidneys, whereas slight differences were observed between the upper and lower anterior liver regions.

DISCUSSION

The study quantified the cCF based on the dose difference between NECT and CECT in abdominal imaging. The mean cCF was approximately 1.5 for the liver, 1.8 for the spleen, and 1.9 for the kidneys, indicating that organ doses during CECT were higher than those during NECT. Therefore, to more accurately estimate radiation dose in CECT, the NECT dose should be multiplied by the cCF. In other words, using

the same dose value for both NECT and CECT leads to an underestimation of the actual radiation dose in CECT.

Previous studies have shown that the increase in CT attenuation values after iodinated contrast administration is primarily due to the photoelectric effect, which also contributes to elevated radiation dose.^[17-19] The photoelectric effect involves the ejection of an electron by an incident photon and is more pronounced in atoms with high atomic numbers, such as iodine.^[20,21] Increased iodine concentration

raises the effective atomic number of tissues, enhancing X-ray absorption and thus organ dose. When low tube voltage is used, radiation dose differs depending on whether an equivalent amount of iodine is administered compared with that at 120 kVp or adjusted to achieve comparable enhancement. Under conditions of equivalent iodine administration at low tube voltage and 120 kVp, higher enhancement is observed at low tube voltage than at 120 kVp due to the increased contribution of the photoelectric effect, resulting in higher cCF values. The contrast conversion factors (cCFs) in dual-energy CT (DECT) depend on the acquisition technique. Dual-layer detector systems typically operate at 120 or 140 kVp, yielding cCF values that depend on the selected tube voltage. In contrast, dual-source and rapid kVp-switching systems yield cCF values that depend on the X-ray photon energies of the two tube voltages used. Nevertheless, regardless of the DECT system, cCF values remain unchanged even when the displayed energy of virtual monochromatic images is varied after CT acquisition. These issues require further investigation in future studies.

Reducing the amount of iodinated CM helps to limit the increase in radiation dose associated with iodine absorption. The low tube voltage technique is effective in reducing radiation dose during CECT. One study reported that normalized organ doses at 80 kVp were significantly lower than those at 120 kVp across all organs (e.g., liver: 1.6 vs. 1.9; pancreas: 1.5 vs. 1.8; spleen: 1.7 vs. 2.0) during CECT. The authors concluded that a low tube voltage protocol combined with a reduced CM volume significantly decreases organ doses, even when using the same volume CTDI, compared with a standard CM protocol. The low tube voltage technique not only enables a reduction in CM volume for patients with impaired renal function but also reduces radiation exposure in patients with high radiation sensitivity.

The risk of radiation-induced cancer from CT scans varies depending on the radiation dose, which is influenced by factors such as the clinical purpose, anatomical area, and the patient's sex and age. For example, in a multinational cohort study of individuals under the age of 22, an association was observed between cumulative radiation dose to active bone marrow and the risk of hematological malignancies.^[5] The excess relative risk was 1.96/100 mGy, with similar estimates reported for both lymphoid and myeloid cancers. Based on a mean dose of 8 mGy per scan, it was estimated that 1–2 out of every 10,000 children undergoing CT today may develop a radiation-induced hematological malignancy within 12 years.^[5] Another study reported an increased risk of childhood brain tumors following exposure to radiation from CT.^[6] Those who underwent at least one head or neck CT scan had a higher likelihood of developing brain tumors compared to unexposed individuals (odds ratio [OR] = 2.84). These findings suggest a positive association between head/

neck CT imaging and the risk of childhood brain tumors. Although the cCFs do not directly predict radiation-induced cancer risk, improving the accuracy of radiation dose assessment is essential. The cCFs are therefore expected to provide at least a modest contribution to this process.

The cCFs are not intended for routine clinical reporting at this stage. The cCF values are dependent on the scan protocol-, CT vendor-, and X-ray photon energy and should be regarded as reference estimates rather than universal correction factors. To implement the cCF values in clinical practice, the necessary simulation data should be acquired at the time of CT system installation or during subsequent system updates. Alternatively, the sharing of relevant information by the CT vendors is also considered to be an important key factor for the widespread future utilization of cCFs. The cCF is not intended to replace SSDE and effective dose metrics, as the two metrics are designed for different purposes. Because SSDE and effective dose metrics do not account for CECT, we believe that the cCF values may provide complementary information to SSDE in CECT.

There were several limitations to this study. First, measurements were taken from the right lobe of the liver. Radiation doses measured in other regions, either inside or outside the liver, may yield different effects on dose reduction. Second, the contrast correction factor was calculated based on a tube voltage of 120 kVp. However, cCF values may vary at different energy levels, such as lower tube voltages, and further studies using a range of tube voltages are warranted. In addition, iodine distribution modeling and tissue composition during contrast enhancement may contribute to uncertainty in organ dose estimation. Finally, the number of patients included in the study was relatively small and the mean relative margin of error for CECT, defined as the half-width of the CI divided by the mean, was 12.08%. When the relative margin of error is reduced to 10% and 5%, sample sizes of 45 and 179 are required, respectively. To improve estimation precision, larger-scale studies and multi-center studies are needed to validate our findings.

CONCLUSION

This study determined contrast conversion factors (cCFs) based on the dose differences between NECT and CECT for abdominal organs. Application of these cCFs enables more accurate radiation dose assessment in CECT for abdominal examinations and may contribute to improved dose estimation in clinical practice.

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Ethical approval: This retrospective study was approved by the local institutional review board Kumamoto University Hospital, Kumamoto, Japan. approval number: 1094 dated on March 11, 2016.

Declaration of patient consent: Patient's consent is not required as patients identity is not disclosed or compromised.

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Conflicts of interest: There are no conflicts of interest.

Use of artificial intelligence (AI)-assisted technology for manuscript preparation: The authors confirm that there was no use of artificial intelligence (AI)-assisted technology for assisting in the writing or editing of the manuscript and no images were manipulated using AI.

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