Radiation Dose Optimization in CT Imaging: Techniques and Best Practices

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Abstract:
As CT tests have become more common, concerns about the radiation hazards they pose have also grown. In this regard, optimizing CT radiation dosage has been a major emphasis for radiologists, referring physicians, technologists, and physicists. Dose-saving strategies are always evolving in two areas: imaging techniques and dosage management. Justifying the medical need of each scan is a crucial first step. Some basic recommendations for reducing exposure include customizing a scan for each patient, cutting down on scan duration, employing tube current modulation, minimizing tube current, minimizing tube potential, iterative reconstruction, and frequently evaluating CT results. This review article will provide an update on how to optimize CT dose in order to improve the benefit-to-risk ratio of this therapeutically useful diagnostic imaging method. This review article's goal is to provide an overview of the fundamentals of CT radiation exposure while highlighting the necessity of optimizing CT radiation doses through the use of new technologies and scanning parameter modifications.

Keywords: computed tomography dose index volume (CTDIvol), the dose-length product (DLP), "as low as reasonably achievable (ALARA)", Tube current modulation (TCM),

INTRODUCTION:
In medicine, computed tomography (CT) scans have grown in importance and use. The frequency of CT tests is increasing daily. Since the introduction of the multi-section CT, CT scanning has greatly increased in speed and z-axis coverage. In our practice, this has resulted in a notable increase in clinical value for both general and more recent applications, including dual energy CT and cardiac CT. As CT is used more often, concerns about the radiation hazards are mounting. In fact, throughout the past ten to fifteen years, the average annual effective dose from medical treatments has grown internationally. Protection from ionizing radiation is crucial due to the danger of cancer. Furthermore, a study found that medical radiation exposure varies by country, with highly industrialized countries having greater

amounts. According to the International Atomic Energy Agency (IAEA), patients should only receive the minimal amount of radiation exposure during diagnostic medical procedures in order to achieve the necessary diagnostic or interventional aims.

The primary concern is that the health of the patient may suffer if any form of ionizing radiation is used during an examination. The harmfulness of radiation exposure depends on the dose given, the radiation's intensity, and the tissue or organ's radiosensitivity. Consequently, any possible deterministic effects must be minimized. Deterministic effects, such as erythema or epilation, which would occur during CT tests, start to show up over a certain threshold. Because CT tests are becoming more and more common, it's important to utilize and understand this ionizing radiation-based imaging technique. In addition to its deterministic effects, radiation's stochastic nature can have detrimental effects on healthy tissue, even at very low doses. This influence can be random regardless of any threshold. The most talked-about stochastic impact is cancer induction. The patient is at greater risk for tests that call for larger doses since the chance that it will happen rises with the amount.

As such, the cancer risk associated with these tests must be taken into account. The overall stochastic risk from CT examinations is evaluated and expressed as the proportionate increase in a patient's lifetime cancer risk. Usually, cancer risk coefficients for the general population are provided in equipment instructions given by manufacturers to assist physicians in this endeavor. Accordingly, in the absence of precise information of technical determinants, which are usually not disclosed, risk assessments for specific patients estimate a population-based average risk, which may not be entirely true for each patient individually.

The computed tomography dose index volume (CTDIvol) and the dose-length product (DLP) are two crucial metrics for optimizing radiation doses in CT images during radiotherapy. They provide exposure reference values but are not directly related to patient dosages. During CT scans, DRLs are crucial for limiting patient exposure and ensuring precise treatment.

A notable improvement in the velocity and z-axis coverage of CT scans has been observed with the introduction of multi-slice CT. As a result, CT's clinical usefulness has greatly increased in our medical practice, including both traditional and cutting-edge applications like dual-energy and cardiac CT. Concern over the radiation hazards of CT scans is growing along with the number of CT scans performed. In fact, throughout the past ten to fifteen years, the average yearly effective dosage per person from medical treatments has nearly quadrupled worldwide. Additionally, a research found that medical radiation exposure is disproportionately distributed, with higher amounts in highly industrialized countries.

For example, statistics from the United States in 2006 showed that almost half (3.0 mSv) of the total radiation exposure (5.6 mSv) came from medical imaging. CT is the main source of radiation exposure in medicine. The number of CT scans in the US is increasing by around 10% per year. This growth rate is much more noticeable in South Korea, where it ranges from 11% to 31% every year.Many techniques to lower CT doses have been developed in response to growing concerns about possible radiation risks from CT. Therefore, by using these cutting-edge imaging techniques, the benefit-risk ratio related to CT exams may be maximized.

While there are many unknowns in estimating lifetime risks from CT scans, the total CT radiation exposure should be kept to a minimum, especially for younger persons who are much more radiosensitive and have longer life expectancies than older persons. In order to encourage a more prudent use of CT imaging, this article will examine the current dose-saving techniques in the field.

CT DOSE PARAMETERS

Understanding CT dosage factors including tube potential, tube current, pitch, weighted CT dose index (CTDIw), volume CT dose index (CTDIvol), dose-length product (DLP), and effective dose is crucial for radiation dose optimization. Reducing radiation exposure while maintaining the diagnostic quality of CT scans is the main goal of dose optimization. Therefore, in the context of dosage optimization, it is critical to determine the prerequisites for obtaining diagnostic-quality CT images. Image noise, image contrast, spatial resolution, and artifacts are the four basic components that determine the quality of CT images. In theory, the square of picture noise and radiation dosage is inversely correlated. In addition to being greatly improved by the use of contrast agents, tube potential also affects image contrast in some materials with high atomic numbers, like iodine, because of differences in photoelectric interactions. The required CT picture quality varies slightly depending on the diagnostic job. As a result, the required dose of CT radiation varies accordingly and should be tailored to the specific therapeutic indications. Low-dose CT, for example, can be used to find high-contrast lesions like lung nodules, colonic polyps (virtual colonography), or urinary calculi.

STRATEGIES FOR OPTIMIZATION OF CT DOSE

According to the "as low as reasonably achievable (ALARA)" concept, a rationale for CT exams must be shown before they are performed. Together with the referring doctors, radiologists are supposed to play a crucial consultative role in this situation. Alternative imaging methods that either do not use ionizing radiation or use less of it, such as sonography, magnetic resonance imaging (MR imaging), or radioactive voiding cystography, should be used in place of CT where comparable or better diagnostic results are expected. On the other hand, when CT is considered required, radiologists must make every effort to reduce the radiation dose related to CT exams while maintaining diagnostic integrity.

One straightforward way to achieve this goal is, for example, to limit the scan range of CT exams to the necessary degree. Precontrast imaging should only be used in multi-phase CT procedures when postcontrast scans are unable to provide diagnostic information from precontrast pictures, and the frequency of repeated scans should be reduced. The therapeutic rationale and imaging techniques for perfusion CT must be carefully developed due to the substantial radiation dose involved. Other successful CT dosage reduction techniques, together with new developments, are described in the following sections. A checklist for optimizing CT dosage

Body Size-Adapted CT Protocols

The purpose of body size-adapted CT protocols is to adjust imaging settings according to each patient's unique body size features. In order to protect patients and ensure accurate diagnosis, these methods seek to maximize picture quality while reducing radiation exposure. Body size adaptation has emerged as a key component of contemporary CT procedures due to growing worries about radiation-induced hazards and the requirement for accurate imaging.

Tube Current Modulation

By lowering the CT dosage in accordance with body size, shape, and attenuation without sacrificing picture quality, tube current modulation significantly aids in CT dose optimization. The tube current can be changed in the z-axis, the x-y plane (angular mode), or both. It has been shown that tube current manipulation can reduce CT doses in adults and children by 26–50%. A complex method used in computed tomography (CT) imaging to maximize radiation exposure while preserving picture quality is called tube current modulation (TCM). It guarantees that patients get the least amount of radiation required for accurate diagnosis and is a fundamental component of dose optimization systems. This method adapts the radiation dosage to each patient's demands by dynamically adjusting the X-ray tube current depending on the patient's anatomy and attenuation characteristics. Modulating the tube current (measured in milli amperes, or mA) during the CT scan is the basic idea of TCM. A consistent tube current across the body would provide an unequal dosage distribution because various body components attenuate X-rays in different ways. For example, denser parts like the belly or pelvis require more radiation than places with less attenuation, such the lungs. To maintain constant image quality, TCM adjusts the current in real-time, lowering the dosage in less dense areas and raising it in denser ones. TCM Types: X-ray tube rotation: This type of rotational modulation alters the tube current using the X-Y plane. For example, when the CT beam passes through the lungs rather than the shoulders or spine, a CT scan of the chest requires less radiation. The Z-Axis Modification of the current as it passes through the body is known as longitudinal modulation. For example, during a scan from the chest to the belly, the tube current increases in denser regions, like the liver, and decreases in less dense regions, like the lungs. Combined Modulation: This technique combines rotational and longitudinal modulation for more accurate dose management. It is particularly effective at delivering constant picture quality throughout complex anatomical regions.

In CT imaging, tube current modulation (TCM) has a number of benefits. The considerable decrease in radiation exposure is one of its main advantages. TCM guarantees that only the required amount of radiation is utilized by modifying the tube current to fit the patient's anatomy, which can result in dosage reductions of up to 40–60% when compared to fixed-current approaches. TCM compensates for differences in tissue density by varying the current as needed for various body areas, maintaining consistent picture quality even at lower radiation doses. Additionally, by taking into consideration each patient's size, form, and distinct anatomical features, TCM offers a highly customized approach to imaging. TCM is frequently used in regular CT scans of the head, chest, abdomen, and pelvic in clinical practice. It is especially helpful in circumstances like paediatric imaging and repeat scans where reducing radiation exposure is crucial. TCM improves patient safety while guaranteeing precise diagnostic outcomes by striking a balance between dosage reduction and picture quality.

Optimal Tube Voltage

In diagnostic radiology, the ideal tube voltage, also known as the kilo-voltage peak (kVp), is a crucial factor that has a big influence on patient dosage and picture quality. The voltage across the anode and cathode of the X-ray tube determines the maximum energy of X-rays that may be generated in the tube. In order to balance radiation dosage, picture contrast, and resolution, the right tube voltage must be chosen. Greater penetrating power X-rays, which are appropriate for imaging denser body areas like the chest, pelvis, or belly, are produced by higher tube voltages. However, because high tube voltage increases scatter radiation, it can decrease picture contrast, especially in soft tissues. On the other hand, lower tube voltages produce X-rays with less energy, which improve contrast for imaging soft tissues like mammography. However, they might not be able to sufficiently penetrate denser structures, which could result in pictures that are underexposed.

The size of the patient, the particular imaging modality, and the clinical rationale all influence the tube voltage selection. For example, to maximize contrast-to-noise ratio (CNR) and minimize radiation exposure during computed tomography (CT), the tube voltage is frequently changed according to the patient's body habitus. Improvements in detector technology in digital radiography enable lower tube voltages without sacrificing image quality. The contrast material used in imaging investigations also affects the ideal tube voltage. Lower tube voltages improve contrast enhancement for iodine-based contrast because they promote photoelectric absorption at lower energy levels. To enhance vascular visibility during CT angiography, this concept is applied.

Considering the anatomy of the patient and the intended imaging results, automatic tube voltage selection algorithms are frequently used in modern imaging systems. These technologies, when paired with iterative reconstruction methods, allow for customized imaging regimens that adhere to the ALARA (As Low As Reasonably Achievable) concept to assure patient safety while achieving diagnostic accuracy.

Scanning Modes

Clinical CT examinations provide a range of scan modalities designed to meet certain diagnostic requirements. These include spiral scanning (with or without ECG synchronization), dual-energy spiral scanning, and sequential scanning (with or without ECG synchronization). Every modality has distinct features and related dosage issues that affect how they are used and how safe they are in clinical settings. Two important dose-related problems in CT imaging are over-beaming and over-ranging. When the X-ray beam's width marginally surpasses the detector array to guarantee full coverage, this is known as over beaming and exposes the imaging region to radiation. However, in spiral scanning, over ranging occurs when the scan duration goes beyond the target region to allow for interpolation during picture reconstruction. Both phenomena contribute to increased radiation exposure, necessitating optimized protocols to minimize their impact while maintaining diagnostic image quality.

In cardiac CT imaging, retrospective ECG-Gated Spiral Scanning is a popular method. In this method, the ECG is recorded concurrently with continuous data gathering across several cardiac cycles. By allowing for the variable retroactive selection of particular cardiac phases for reconstruction, this method makes it possible to thoroughly assess the movements and structures of the heart. However, compared to other modes, continuous acquisition exposes users to more radiation, therefore dose-reduction techniques such tube current regulation are crucial.

A less expensive option for cardiac imaging is prospectively ECG-Triggered Sequential Scanning. This technique, in contrast to retrospective gating, only takes pictures when the ECG data triggers certain cardiac cycle stages. This focused strategy preserves diagnostic accuracy while drastically lowering radiation dose. However, in comparison to retrospective scanning, it necessitates exact timing and is less adaptable for assessing dynamic heart motion.

An important development in CT technology is High-Pitch Dual Source Spiral Scanning. This mode uses two X-ray tubes and detectors working together to acquire images very quickly and with very little motion artefacts. Because the high pitch enables whole heart scans in a single beating, it is very useful for cardiac imaging. Patients with irregular heart rhythms or limited breath-hold capacity can benefit from this quick acquisition since it minimizes radiation exposure and the requirement for breath-holding.

Two distinct X-ray energy levels are used in dual-energy scanning to improve material separation and tissue characterization. This technique is quite useful for things like detecting gout crystals, distinguishing between kidney stones, and enhancing contrast in vascular imaging. Also, dual-energy CT reduces the need for extra scans and contrast dosages by enabling iodine measurement and virtual non-contrast imaging. Although this method has benefits, it necessitates certain technology and software, which not all clinical settings may have.

By enhancing picture quality without raising radiation dosage, noise-reducing image reconstruction algorithms have completely changed CT imaging. By successfully reducing noise, methods like deep learning-based reconstruction and iterative reconstruction improve picture clarity and diagnostic precision. High-quality imaging is made possible by these algorithms, which are especially helpful in low-dose protocols that follow the "as low as reasonably achievable" (ALARA) guideline for radiation exposure.

Lastly, a thorough three-dimensional perspective of cardiac anatomy is offered by volume-rendered cardiac CT scans, which allow for a close examination of the heart's chambers, coronary arteries, and surrounding tissues. These pictures, which are frequently created using information obtained in the above three modalities, are very helpful for non-invasive coronary artery disease evaluation and preoperative planning. For example, a foot perspective provides a special viewpoint for assessing the spatial interaction between cardiac components.

Miscellaneous Methods

Particularly helpful in paediatric and cardiac CT scans, beam-shaping filters (such as bowtie filters) can lower the amount of radiation absorbed in the scanned body's periphery. Radiation exposure to radiation-sensitive organs, including the thyroid, breast, and eye lens, can be reduced by 20–50% using in-plane shielding. However, shields are linked to streak artifacts, higher attenuation levels, and increased picture noise. Placing the shield after acquiring a scout image results in a larger dosage decrease when utilized with tube current modulation. For hygienic and financial reasons, shields are not frequently utilized. However, with the recent development of organ-based tube current regulation, it was possible to reduce the dosage to the anterior radiosensitive organs by 27–50% for head and chest CT scans without increasing picture noise or requiring shields. By making up for the increased picture noise brought on by a low radiation dosage, greater contrast enhancement can be utilized as a dose-saving strategy for contrast-enhanced CT exams.

METHODOLOGY

This review-based paper's approach was created to methodically find, choose, and evaluate pertinent material in order to meet the study's goals. A thorough search was carried out utilizing a combination of keywords and topic-specific Boolean operators across many databases, including PubMed, Scopus, and Web of Science. Predetermined inclusion and exclusion criteria served as the basis for the search approach, which concentrated on English-language studies that were pertinent to the population or condition being studied and published during the previous 10 years. Conference abstracts, non-peer-reviewed articles, and articles with insufficient data for analysis were all disqualified.

After identifying potentially pertinent papers through the screening of titles and abstracts, the entire texts were carefully examined to verify eligibility. To ensure transparency and reproducibility, the research selection procedure was documented using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) standards. Using a standardized form, data extraction was carried out; recording important details such the study's design, sample size, methods, results, and noteworthy discoveries.

CONCLUSION

In order to weigh the possible hazards against the diagnostic benefits of CT imaging, radiation dose optimization is crucial. Healthcare professionals can accomplish large dosage reductions while retaining picture quality by utilizing sophisticated techniques like as TCM, iterative reconstruction, and patient-specific procedures. To increase patient safety in CT imaging, radiologists, technicians, and physicists must work together and adhere to the ALARA principle.

REVIEW OF LITATURE

1. **Whitebird, et al. (2022)** Strategies for dose optimization: views from health care systems. Journal of the American College of Radiology, 19(4), 534-541.
   Summary: The paper identifies seven organizational strategies for optimizing radiation dose in CT imaging, such as engaging radiologists and technologists, establishing a CT dose committee, managing organizational change, providing leadership, monitoring and benchmarking, modifying protocols, and implementing equipment/work rule changes.
2. **Mohd A. (2024)** Optimization of CT radiation dose: Insight into DLP and CTDI. Future Health, 2024.
   Summary: Highlights the role of CTDI and DLP in radiation dose monitoring and optimization, emphasizing parameter adjustment and advanced technologies to maintain image quality while reducing dose.
3. **Rao, S., et al. (2024),** Advanced Computational Methods for Radiation Dose Optimization in CT.
   Summary: Discusses dose optimization methods for head, neck, and pelvis CT scans, noting significant reductions in CTDIvol, DLP, and effective dose by applying optimized protocols based on DRLs.
4. **Larson, et al. (2024)**, A Vision for Global CT Radiation Dose Optimization. Journal of the American College of Radiology.
   Summary: Describes a global vision for CT dose optimization, recommending quality-based target doses and continuous optimization supported by local radiology teams and process control programs.
5. **Dewi, et al. (2024)**, CT image quality and dose optimization by combining tube voltage, dose reduction setting and ASIR-V (explorative study using VCT phantom). Journal of Applied Research and Technology, 22(3), 441–450. https://doi.org/10.22201/icat.24486736e.2024.22.3.2343
   Summary: Demonstrates optimization of CT radiation dose by adjusting tube voltage, applying dose reduction settings, and using ASIR-V software, with careful balancing of radiation dose and image quality.

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