



**Arab American University
Faculty of Graduate Studies**

**Radiation Dose Evaluation for Pediatric Patients
Undergoing Repeated Brain Computed Tomography
Examination**

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**This thesis was submitted in partial fulfillment of the
requirements for the Master's degree in CT and MRI
Sciences
Feb /2026**

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Thesis Approval

“Radiation Dose Evaluation for Pediatric Patients Undergoing Repeated Brain Computed Tomography Examination”

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This thesis was defended successfully on 12-2-2026 and approved by:

Committee members

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Three handwritten signatures in blue ink are displayed. The first signature is a stylized 'M' with a horizontal line. The second signature is 'abed alasi' written in a cursive style. The third signature is 'O. A. Khodrog' written in a cursive style.

Declaration

I certify that this thesis is my original work, properly cited, and has not been part of another person's thesis or dissertation that was turned in for a degree, diploma, or other credentials.

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Date: 26.4.2026

Dedication

This thesis dedicated with heartfelt sincerity and gratitude, first, to my beloved daughter, who has always been a source of strength and inspiration for me. To my dear parents and siblings, who supported me both financially and emotionally, and were the source of my determination to overcome every obstacle. In addition, I cannot forget my professors and colleagues, who spared no effort in providing me with information and assistance to complete this educational journey.

I pray that God rewards you all with the best and blesses you for all the support and love you have given me.

Acknowledgment

First, I would like to thank Allah, the Almighty, and praise Him for facilitating my efforts in completing this work.

My heartfelt thanks go to my supervisor, Dr. Mohammed Al Jamal, for his constant support, advice, encouragement, and assistance at every stage of the project from its inception to its completion, whether through writing or practical work.

I also want to express my gratitude and appreciation to everyone who helped me during the data collection process and work in the hospitals included in the study.

A big thank you to my family, who supported me in every possible way and to my daughter, who endured my absence during this time.

I extend my thanks to the Arab American University and all its staff.

Lastly, to everyone who contributed, whether directly or indirectly, in small or large ways, to the completion of this thesis, I offer my sincere gratitude. Your contributions have had a significant impact on this work, and I am deeply grateful.

Abstract

Introduction: Children with neurological conditions often need repeated CT scans, which creates concerns about the long-term effects of accumulated radiation exposure. Additionally, because clinical practice varies, it is essential to optimize CT protocols.

Purpose: This study aimed to compare scanner-recorded and calculated doses with estimates from standard pediatric and adult protocols, analyze how scan parameters changed across patient groups, evaluate CTDIvol, DLP, and effective dose in children undergoing repeated brain CT scans, and explore options for dose optimization.

Methods: This retrospective study examines the radiation exposure associated with 68 pediatric patients who underwent two to four brain CT scans at Rafedia Surgical Hospital from 2021 to 2024. We used statistical analyses (correlations, Friedman test, paired tests) to compare dose indicators, examine changes across scans in different groups, and assess relationships between variables.

Results: The findings of the study showed that the total effective dose increased as the number of scans increased. In addition, it found significant differences ($p < 0.001$) between scanner-calculated effective doses and those estimated from pediatric and adult protocols. Clinical practice doses were much closer to the adult protocol estimates than to the pediatric estimates. If clinical practice followed the pediatric protocol more closely, the dose could reduce by about 13%.

Conclusion: Repeated pediatric brain CT scans risk substantial radiation dose increases, especially after the second scan. Current practice often utilizes an adult setting instead of appropriate pediatric protocols. Adhering to optimized protocols and thoroughly justifying each repeat scan is essential to minimize children's radiation exposure.

Keywords: Pediatric Brain CT, Repeated Scans Radiation Dose, Effective Dose, CTDIvol, DLP, Protocol Optimization and Radiation Protection.

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List of Abbreviations

AAUP: Arab American University of Palestine
ACR: American College of Radiology
AI: Artificial Intelligence
ALARA: As Low As Reasonably Achievable
ATCM: Automatic Tube Current Modulation
BEIR: Biological Effects of Ionizing Radiation
ciTBI: Clinically Important Traumatic Brain Injury
CNNs: Deep Convolutional Neural Networks
CT: Computed Tomography
CTDIvol: Computed Tomography Dose Index Volume
CTS: Computed Tomography Scan
DLR: Deep Learning Reconstruction
DLP: Dose Length Product
DMMS: Dose Monitoring and Management Systems
DRLs; Diagnostic Reference Levels
ED: Effective Dose
ESNR: European Society of Neuroradiology
ESPR: European Society of Pediatric Radiology
FDA: Food and Drug Administration
GCS: Glasgow Coma Scale
ICRP: International Commission on Radiological Protection
IniCT score: Initial CT Scan Score
kVp: Kilovoltage Peak
LDRLs: Local Diagnostic Reference Levels
LNT: Linear No-Threshold Model
mA: Milliampere
mAs: Milliampere-Second
mGy: Milligray

mGy·cm: Milligray Centimeter

mm: Millimeter

MoH: Ministry of Health

MRI: Magnetic Resonance Imaging

MSAD: Multiple-Scan Average Dose

mSv: Millisievert

mTBI: Mild Traumatic Brain Injury

NCRP: National Council on Radiation Protection and Measurements

PCD-CT: Photon-Counting Detector Computed Tomography

PECARN: Pediatric Emergency Care Applied Research Network

PMMA: Polymethyl Methacrylate

POCUS: Point-of-Care Ultrasound

REID: Risk of Exposure-Induced Cancer Death

RHCT: Repeat Head Computed Tomography

TBI: Traumatic Brain Injury

US: Ultrasound

USA: United States of America

Chapter One :Introduction

1.1 Background

The advancement of CT technology has continued progressively over the decades. The introduction of MDCT systems allowed much faster scan times and higher spatial resolution. This advancement is particularly relevant in pediatrics, where minimizing motion artifacts is essential because children often struggle to remain during scans. This technological evolution has continued at a rapid pace (Kalender, 2011).

Today, CT plays a central role in diagnosis, treatment planning, and follow-up in a wide range of clinical fields such as cardiology, oncology, emergency medicine, and trauma. Large volumetric datasets can now be captured in a matter of seconds, revolutionizing how doctors track illness and make quick diagnostic decisions. Another significant advancement is the emergence of hybrid modalities, such as PET-CT, which combine anatomical and functional imaging. This integration has expanded CT's diagnostic utility by providing both structural and metabolic information in a single exam (Townsend, 2008).

Although CT is a valuable diagnostic modality, its increasing use has raised concerns about the potential risks of cumulative radiation exposure. With the increasing use of ionizing radiation in diagnostic and therapeutic medicine in recent decades, there have been concerns among radiologic professionals and the public regarding the possible health effects associated with the absorption of ionizing energy by the body of patients. Sources of ionizing radiation in the environment of man are various and include naturally occurring and man-made sources. The main source of exposure, however, is from natural background, with medical sources being the second contributor to the total dose received by man (Tsalafoutas, 2010).

From medical exposure, CT is currently one of the major contributors to the collective

population radiation dose because it is a relatively high-dose procedure, and an increasing number of people are subjected to CT examinations many times during their lifetime (Tsalafoutas, 2010).

This growing trend in medical imaging has sparked global radiation safety conversations and initiatives. Comprehensive guidelines stressing the prudent and justified use of ionizing radiation in healthcare have been released by organizations such as the IAEA and the ICRP (Guide, 2018).

These recommendations aim to build a culture of radiation safety among healthcare providers, ensuring that the benefits of medical imaging outweigh the potential risks (Valentin, 2007). Campaigns like 'Image Gently' for pediatric imaging and 'Image Wisely' for adult imaging have been started in response to increased awareness of radiation risks in order to encourage radiation protection in these susceptible groups (Strauss et al., 2010).

The rapid increase in CT utilization is primarily due to its high diagnostic accuracy, availability, short acquisition time, and effectiveness as a problem-solving tool. Although remarkable advances in CT technology have greatly enhanced modern medical practice, they have also raised concerns regarding patient safety, as CT exposes patients to relatively higher radiation doses compared with most other diagnostic methods (Brenner & Hall, 2007). Although CT makes up about 17% of imaging exams in the U.S., it contributes nearly half of the total medical radiation dose (Mettler Jr et al., 2009).

Radiation protection in CT based on the ALARA principle, which emphasizes justification and optimization. Justification requires that every exposure is medically necessary and that the expected benefit clearly outweighs the risk. Optimization, on the other hand, focuses on minimizing the patient's dose while maintaining adequate image quality.

Finding the right balance is important; reducing the dose too much can lower image quality, which may lead to incorrect diagnoses or repeated scans, and this increases the patient's total exposure (Goldman, 2007).

Ongoing efforts aim to refine CT techniques and apply modern technologies to achieve high-quality images with minimal radiation dose. Radiologists, radiographers, medical physicists, and referring clinicians are all essential to the patient's radiation journey, and their combined dedication is necessary for the successful implementation of ALARA, which requires them to commit to following best practices, pursuing ongoing education, and keeping up with developments in technology (Valentin, 2007).

Results of recent epidemiologic studies and risk model estimations have predicted an increased risk of cancer associated with CT radiation exposure in radiosensitive children and adolescents. In the United States, among the more than 60 million CT examinations performed each year, pediatric CT scans account for approximately 4-7.1 million examinations (Mettler Jr et al., 2009).

NCRP highlights that the largest contributor to the population dose from medical exposure is computed tomography (CT) examination. The population effective dose of a CT examination is 1.47 mSv¹, while this dose accounts for 49% of the medical exposure in the U.S. Since 1980 up to 2006, the effective dose due to CT examination amplified 92-fold. A high effective dose potentially entails a higher risk of cancer (Schauer & Linton, 2009). Berrington de González and colleagues appraised that about 29,000 (95% uncertainty limits, 15,000–45,000) future cancers could be related to CT scans performed in the U.S (De González et al., 2009).

Children are more radiosensitive than adults are because they live longer and their cells divide more quickly, increasing their vulnerability to radiation effects. They are more vulnerable to the stochastic effects of ionizing radiation, especially the induction of cancer (Brenner & Hall, 2007).

LNT model assumes that any amount of radiation carries a proportional risk of inducing cancer, implying that even the smallest exposures may contribute to long-term health effects. This theory supports the cautious approach to pediatric imaging by highlighting the necessity of minimizing any unnecessary radiation exposure in children. Because radiation risk is cumulative, the lifetime risk increases with each extra exposure, so safe and appropriate CT use in pediatrics is essential (Council et al., 2006).

Similarly, a recent Japanese study estimated that 29.9 million patients undergo CT examinations annually, with pediatric CT scans accounting for 1.43 million of these procedures (Tsushima et al., 2010). Accordingly, the increasing radiation exposure from CT has increased concerns about the health impact of CT scans. Because children's cells divide faster and they live longer, they face higher risks from radiation compared to adults, who are more likely to develop potential radiation injury. The risk of radiation-induced cancer development should be a concern in pediatric patients because it can develop after a long latency period (Brenner & Hall, 2007).

The biological effects of ionizing radiation on human tissues commonly divided into two groups, stochastic effects and deterministic effects. Stochastic effects of radiation related to the occurrence of carcinogenesis and may occur years after exposure. These effects are a risk from exposure to the low levels of radiation used in medical imaging, including CT examinations. Exposure to ionizing radiation is of concern because evidence has linked exposure to low-level radiation at doses used in medical imaging to the development of cancer (Council et al., 2006).

In contrast, deterministic effects occurred at doses much higher than those of typical diagnostic imaging exams, and radiation includes cell death. The damage may be extensive enough to affect tissue and become clinically observable (skin redness, hair loss). Effects of this type are called “tissue reactions ”and will occur only if the radiation dose exceeds a certain threshold (Icrp, 2012).

Children who undergo CT procedures are at higher risk because they are more sensitive to radiation and have a longer life expectancy than adults have. On the other hand, women are at a somewhat higher risk than men of developing cancer after receiving the same radiation exposures at the same ages (Council et al., 2006).

The radiation dose a patient receives from a CT scan depends on many factors, including the patient’s size and the settings used on the CT machine. Key technical factors kVp, scan pitch, the length of the scan area, and mAs. Patient-specific factors like size, age, and body composition also play an important role (Goldman, 2007).

To keep radiation doses as low as possible while still getting good image quality, modern CT scanners use several advanced dose reduction technologies. For example, ATCM adjusts the tube current during the scan based on how much the patient’s body blocks the X-rays, helping to reduce unnecessary radiation. Properly centering the patient in the scanner is also important because if the patient is off-center, it can increase both the radiation dose and image noise (Kalra et al., 2015).

Another major advancement is the use of iterative reconstruction (IR) techniques. These algorithms allow scans to be done with lower radiation doses while still producing clear images by reducing noise, improving on older methods like filtered back-projection (Nagayama et al., 2018).

Looking ahead, new technologies such as dual-energy CT and photon-counting CT offer even better image quality and dose control, promising further improvements in patient safety (Srinivas-Rao et al., 2023).

Monitoring radiation dose accurately is a critical part of radiation safety practices. The DLP and the CTDIvol are the two main dose variables that shown on CT scanners. The mean absorbed dose in the scanned volume is represented by CTDIvol, and the total radiation energy delivered during the examination is estimated by DLP, which is the product of CTDIvol and examination length. These measurements are useful for protocol optimization and quality control, but they reflect the scanner's output rather than the exact dose received by the patient (Kalra et al., 2015).

Estimating patient-specific organ doses and the effective dose usually demands complex methods, frequently utilize computational phantoms or Monte Carlo simulations. According to the overall cancer risk, the effective dose is a weighted average of organ doses (Tsalafoutas & Metallidis, 2011).

However, it is important to note that the effective dose primarily developed for regulatory purposes and population-based risk assessment. Consequently, its applicability for evaluating radiation risk in individual patients remains subject to ongoing debate. Nevertheless, it continues to serve as a fundamental metric in clinical dose optimization studies (McCollough, 2008).

ICRP recommends the use of effective dose for epidemiological investigations and comparative assessments of radiological procedures, while cautioning against its use for estimating individual patient risk (Valentin, 2007).

Brain CT scan commonly used for diagnosis of traumatic head injuries, infections, and other diseases with instability, so it can be associated with a high radiation dose to organs such as lenses, parotid and salivary gland, pharynx, and hypophysis. Brain CT is the most common body part scanned in children (Kanal et al., 2015). Over 10% of CT, examinations in the world performed on patients under 18 years of age. The effective doses of radiation from CT scans may be 5–20 times higher than those from routine conventional radiology (Mettler et al., 2008). On average, predictive studies estimated brain doses of 55 mGy and effective doses of 1.6 mSv per head CT scan for pediatric patients (Sheppard et al., 2018).

The risk of thyroid cancer significantly increased after a mean dose to the thyroid during childhood as low as 0.05 to 0.1 Gy (50 to 100mGy). Nevertheless, there is no dose limit below the risk can excluded. For this reason, irradiating procedures such as CT scans that may deliver up to 10 mSv should be avoided in young children whenever possible, and when performed, they should deliver a minimal radiation dose (Veiga et al., 2016).

To mitigate the risks associated with ionizing radiation, the global health community has emphasized the development of Diagnostic Reference Levels (DRLs) as a key tool for dose optimization. DRLs serve as benchmarks to indicate whether the radiation dose for a specific procedure is unusually high or low; however, they are not regulatory dose limits. Typically, DRLs are established at the 75th percentile of radiation dose distributions derived from extensive clinical practice surveys (Vaño et al., 2017).

Many countries and regions have implemented national or local DRLs for pediatric CT examinations, including head scans, to assist healthcare facilities in auditing their radiation doses and identifying opportunities for dose reduction. These efforts form part of a broader initiative to standardize and enhance pediatric imaging protocols across diverse clinical environments (Alhujaili et al., 2024; Rawashdeh et al., 2019).

Given that DRLs have demonstrated effectiveness in lowering patient radiation doses without compromising diagnostic image quality, they represent an essential component of radiation protection strategies in medical imaging (Kalender, 2014).

Studies from Nigeria (Abdulkadir et al., 2021), Iran (Hanafi et al., 2021; Mohammadbeigi et al., 2019), and Malaysia (Muhammad et al., 2020) highlight the global effort to establish regional standards for pediatric CT doses. Interestingly, while their reported values vary widely, they all emphasize the same conclusion: without local reference levels, hospitals tend to overexpose children.

This insight is particularly useful for Palestine, where no official pediatric DRLs exist yet. Because even within the same country, radiation doses can vary significantly between institutions, so setting local DRLs is especially important. CT technology, imaging protocols, and operator training differences can all account for this disparity (Alhujaili et al., 2024).

By performing dose assessments and then comparing their data to established DRLs, medical centers can fulfill their responsibility to protect those who are most susceptible patients by identifying protocols that deliver excessively high doses and taking corrective action. This continuous process of improving quality is the foundation of modern radiation safety programs. Regular reviews and updates of DRLs are also necessary to reflect advancements in technology and best practices in pediatric imaging (Alhujaili et al., 2024).

Additionally, pediatric imaging made even more challenging by the wide range of patient sizes, from newborns to adolescents. A one-size-fits-all strategy is inappropriate and risky. Therefore, for effective dose control, age-based or size-specific protocols are required. The need for stratified DRLs is highlighted by the numerous studies that demonstrate a direct relationship between the appropriate radiation dose and the patient's size or age (Inoue et al.,

2022).

The neonatal period presents a unique challenge in pediatric radiology. Neonates, particularly premature infants, have the highest radiosensitivity and the longest lifespan for stochastic effects to manifest. Brain CT scans are often required for conditions such as congenital abnormalities, intracranial hemorrhage, and hypoxic-ischemic encephalopathy. Because of its small size, the newborn's head requires careful protocol adaptation to avoid excessive radiation exposure. Standard adult or even older pediatric protocols are totally out of date and can result in overdosing. This makes it necessary to develop special neonatal protocols that match their anatomy and clinical needs (Gottumukkala et al., 2019).

The idea that multiple tiny doses of ionizing radiation can cause cancer was established by many earlier studies on the relationship between cancer risk and repeated diagnostic X-rays. As a result, the absorbed dose that arises from CT scans became a worldwide health concern (Council et al., 2006).

1.2 Problem Statement

Computed Tomography (CT) has become an indispensable diagnostic tool in modern medicine due to its rapid acquisition time, high spatial resolution, and diagnostic accuracy. However, CT utilizes ionizing radiation, which is associated with potential stochastic biological effects, including radiation-induced malignancies. Although the individual risk from a single properly justified CT examination may be low, the cumulative radiation exposure resulting from repeated examinations remains a significant concern, particularly in pediatric populations.

Children are inherently more radiosensitive than adults because of their rapidly dividing cells, higher tissue susceptibility, and longer life expectancy, which extends the period during which radiation-induced effects may manifest. This vulnerability is further amplified in infants and neonates undergoing repeated brain CT scans for conditions such as hydrocephalus, traumatic brain injury, intracranial infections, and congenital abnormalities. In these cases, serial imaging is often clinically necessary for diagnosis, monitoring of shunt function, or assessment of disease progression, leading to cumulative radiation doses that may substantially exceed those from single examinations.

Despite growing international awareness of pediatric radiation protection and the implementation of Diagnostic Reference Levels (DRLs) in many countries, Palestine currently lacks established pediatric-specific DRLs to guide protocol optimization. Moreover, there is limited published data evaluating cumulative radiation dose in neonatal and infant patients undergoing repeated brain CT examinations within Palestinian healthcare institutions. In the absence of standardized national benchmarks and local dose audits, there is a risk that pediatric patients may be scanned using protocols that are not fully optimized for their size and clinical indication, potentially resulting in unnecessary radiation exposure.

Therefore, a critical gap exists in quantifying radiation dose levels, evaluating cumulative exposure from repeated brain CT scans, and assessing whether current clinical practice aligns with pediatric dose optimization principles. Addressing this gap is essential to ensure adherence to the ALARA principle, support evidence-based protocol refinement, and enhance radiation safety for one of the most vulnerable patient populations.

1.3 Justification and Significance of the Study

This study is important because it deals with the safety of pediatric patients. This study assesses radiation dose levels at Rafedia Governmental Hospital, which allows for comparison with national and international Diagnostic Reference Levels (DRLs). The findings may help raise awareness among medical professionals, radiologists, and technologists about the importance of dose optimization. They could also support the development of pediatric-specific CT protocols, contribute to updating national and local DRLs, and reduce unnecessary exposure for children.

To protect the safety and well-being of children patients receiving brain computed tomography (CT) in Palestine, it is crucial to assess the radiation dose. Because children are more sensitive to radiation than adults are, prolonged radiation exposure can raise a child's chance of developing cancer in the future (Brenner et al., 2001). Through radiation dose measurement, medical professionals can guarantee that CT scans are carried out at the lowest feasible radiation level while maintaining reliable diagnostic results (Salah et al., 2023).

The creation of pediatric brain CT diagnostic reference levels (DRLs) made possible by measuring radiation dose. These lessen needless exposure, safeguard children undergoing repeated CT scans, and standardize and optimize dosages for various age and weight groups (Inoue et al., 2022; Khafaji et al., 2023). In short, reducing the long-term risks of radiation in children requires careful monitoring of doses during pediatric brain CT scans.

1.4 Study Objectives

1.4.1 General objective

To measure the radiation dose, using CT dose index and effective dose, in pediatric patients aged two years or younger who undergo repeated brain CT scans.

1.4.2 Specific objectives

- 1) Evaluation of the effective dose for pediatric patients undergoing brain CT examinations, including those with and without contrast media.
- 2) To assess the collective average effective dose from repeated pediatric brain CT scans based on data available at the CT system.
- 3) To measure the radiation dose of brain CT examinations based on CTDI and DLP to obtain the effective dose.
- 4) To compare the measured radiation dose with the values recorded by the CT system.
- 5) To identify technical parameters (e.g., kVp, mAs) that influence dose levels and provide recommendations for optimizing current protocols.

1.5 Hypothesis of Research

The hypothesis is that pediatric patients undergoing repeated brain CT examinations in Palestine, when scanned with suitable protocols, will have the lowest effective radiation dose at a significance level of $\alpha \leq 0.05$.

1.6 Questions of the Research

The main research question:

What is the radiation dose received by pediatric patients undergoing repeated brain CT examinations?

The research sub-questions:

1. What are the average radiation doses received by pediatric patients during repeated brain CT scans?
2. How do different imaging protocols affect the radiation dose in pediatric brain CT procedures?
3. What factors contribute to variations in radiation dose among pediatric patients undergoing repeated brain CT scans?
4. How does the cumulative radiation exposure from repeated brain CT scans affect the long-term health outcomes of pediatric patients?
5. Does the current pediatric brain CT protocol provide effective dose optimization compared with adult-based protocols in pediatric patients?
6. Do radiographers follow pediatric protocols when scanning pediatric patients?

Chapter Two: Literature Review

This chapter reviews scientific studies, published works on CT dose assessment, and presents a variety of techniques that have employed to establish an effective dose. It offers comprehensive coverage of CT radiation dose metrics, factors affecting dose, and the importance of balancing diagnostic accuracy with radiation safety.

2.1 Introduction

CT has become an indispensable diagnostic tool, fundamentally transforming how clinicians visualize internal organs. It is widely preferred for assessing disease severity because it provides rapid, high-resolution, cross-sectional images with anatomical detail far superior to traditional radiography. High-resolution CT is now a standard pre-operative imaging requirement, offering detailed insight into the complex anatomy of the brain and paranasal sinuses as well as the spatial relationships of pathological regions to vital structures (Jibiri & Adewale, 2014).

CT is recognized globally as one of the most important imaging modalities in modern medicine. Unlike standard radiographs, it produces detailed cross-sectional images, fundamentally altering how clinicians assess internal organs, soft tissues, and vascular structures, making CT a preferred diagnostic option in many hospitals. CT scans are useful because they can quickly detect and monitor many medical conditions, guide treatment, help evaluate whether interventions are successful, and sometimes eliminate the need for surgery (Brenner & Hall, 2007).

The clinical applications of CT continue to expand, encompassing oncologic staging, treatment planning, and therapy response monitoring. It is the primary imaging modality used

in neurological disease to treat traumatic brain injury and acute stroke. For the diagnosis of coronary artery disease, CT angiography (CTA) has become a non-invasive substitute for traditional angiography in cardiology. In emergency and trauma situations, where prompt and thorough evaluation is essential for patient survival, the speed of contemporary multi-detector CT (MDCT) scanners has also made them indispensable (Tack et al., 2012).

However, the rapid growth in CT utilization has heightened awareness about radiation exposure risks among healthcare professionals and the public alike. Professionals working with CT, such as radiologists, technologists, medical physicists, and others, should consider three key questions: Why are CT doses high? What dose of patients receive in my facility? And how can these doses be reduced to protect patients and staff? (Pearce et al., 2012).

Although these questions are significant for several reasons, radiation risks are the primary factor in understanding radiation dose in CT. The concern is greater in children because, as mentioned earlier, they are more radiosensitive than adults due to their rate of cell division, and they live longer, giving more time for radiation-related cancers to appear (Pearce et al., 2012).

2.2 The Development of CT Scanners: A Generational Path to Lowering Doses

The evolution of CT technology has centered on three key objectives: faster image acquisition, enhanced image quality, and lower radiation exposure. Historically, CT advancements have been categorized into distinct “generations,” each defined by significant changes in scanner design and data acquisition techniques (Kalender, 2011).

The second-generation system introduced a narrow fan beam to accelerate scanning, reducing acquisition time to less than one minute per slice. More patients could now undergo

CT thanks to this design's significant scan time reduction, but scattered radiation increased. The third-generation wide fan-beam design became the foundation for most modern CT scanners. By reducing scan times to only a few seconds per rotation, it significantly minimized motion artifacts, allowing for faster and more reliable brain imaging (Kalender, 2011).

The fourth-generation “stationary ring” system incorporated a full 360° array of detectors. Although it aimed to minimize image artifacts observed in third-generation models, the design was more expensive and mechanically complex, offering no substantial improvement in scan speed or dose efficiency. The current generation is characterized by fundamental changes in data processing and acquisition, which are more closely related to dose reduction than by mechanical changes (Kalender, 2011).

The fifth generation, known as helical or spiral CT, introduced volume scanning, enabling entire organs such as the brain to be imaged in a single continuous rotation. This made dose modulation possible, which was a crucial step in lowering the dose for younger patients because it allowed the radiation output to be automatically adjusted to the patient's anatomy (Kalender, 2011).

The sixth-generation multidetector CT (MDCT), often called the “slice revolution,” allowed for faster acquisitions and high-resolution image reconstruction from a single axial rotation. According to this, along with sophisticated iterative reconstruction algorithms, physicians can use a great deal less radiation while preserving diagnostic quality (Kalender, 2011).

The seventh generation, characterized by dual-energy and photon-counting CT technologies, enables the extraction of detailed spectral information from the X-ray beam.

These innovations improve the balance between image quality and radiation dose, enhancing diagnostic precision while improving patient safety (Kalender, 2011).

2.3 Physical Principles of Computed Tomography (CT)

A CT system consists primarily of three main components. The first one is the gantry, which is the large circular structure that holds the X-ray tube and detector array; this structure rotates rapidly around the patient. The second component is the patient table, the part that the patient lies on and moves through the gantry aperture to scan the required part of the body. And the last one is the computer system, which is considered the brain of the machine, it processes attenuation data collected by detectors and converts it into digital images using complex mathematical algorithms, known as reconstruction (Seeram, 2015).

The interaction of X-rays with tissues depends primarily on each tissue's density and atomic number. As X-rays traverse the body, they are absorbed or scattered to varying extents, creating measurable differences in attenuation. Air in the lungs has low attenuation, allowing most X-rays to pass through, and thus appears dark on the image. In contrast, bone tissue, with high attenuation, absorbs more radiation and appears bright white. There is a gray area between two extremes where soft tissues like the liver and brain are located. After the radiation has passed through the body, the detectors measure its intensity from thousands of different angles as the tube rotates (Romans, 2025).

Each CT image represented as a digital matrix of pixels (picture elements). Every pixel corresponds to a voxel (volume element), which means a small three-dimensional portion of tissue whose numerical value reflects the average X-ray attenuation within that volume. The values above are expressed in Hounsfield Units (HU), a standardized scale that defines tissue radiodensity, with water having a value of 0 HU, air having a value of -1000 HU, and dense bone having a value of +1000 HU or higher. This scale enables physicians accurately

differentiate between different tissue types, which is critical for disease diagnosis (Goldman, 2007).

With the continued improvement of tomography technology, a new technique developed called MDCT, which uses many rows of detectors to scan a larger area of the body in a single rotation. This improved image reconstruction in multiple planes three dimensional (3D) and drastically shortened scan times, but it also brought up fresh worries about increased radiation exposure (Valentin, 2007).

2.4 Brain CT Scan

CT scans provide high-resolution images and are one of the most important medical advances of the 20th century. They continue to be a go to tool in neurology and neurosurgery for both sudden and long-term conditions. When it comes to the brain, CT scans are especially helpful for spotting and managing problems like bleeding inside the skull, head injuries, tumors, and strokes, especially those caused by bleeding. Because CT images are so clear, doctors can accurately pinpoint where the problem is and tell different types of brain issues apart, which helps them make quick and effective treatment decisions. In emergencies, CT scans are especially valuable because they are fast and reliable (Jibiri & Adewale, 2014).

According to the consensus recommendations from the ESNR and the ESPR, US is established as the primary imaging modality of choice for evaluating the infantile brain. It is preferred over CT in the initial assessment due to its excellent safety profile, lack of ionizing radiation, and the ability to perform bedside examinations without the need for sedation, provided that a state-of-the-art technique is utilized, MRI is generally preferred when detailed soft-tissue characterization is required, offering superior contrast resolution without radiation exposure (Rossi et al., 2023).

Point-of-Care Ultrasound (POCUS) has demonstrated high diagnostic accuracy for detecting superficial skull fractures in children with minor head trauma and can be performed rapidly at the bedside by trained emergency physicians. While POCUS may reduce the need for CT scans in selected low-risk cases, computed tomography remains the gold standard for detecting intracranial injuries and more complex fractures. Therefore, incorporating POCUS as a preliminary screening tool could help limit unnecessary radiation exposure in pediatric patients, supporting ALARA principles, without compromising clinical care (Dehbozorgi et al., 2021).

Although cranial ultrasound is the primary imaging modality in neonates due to its safety profile and absence of ionizing radiation, it has inherent limitations. Ultrasound is operator-dependent and restricted by acoustic windows, while MRI, although superior in soft tissue characterization, may not always be readily available in emergency settings and often requires sedation. In such situations particularly in acute neurological deterioration or when rapid assessment is required CT plays a critical complementary role. CT remains widely used in pediatric neuroimaging for specific clinical indications where speed, accessibility, and evaluation of bony structures or acute hemorrhage are essential (Ní Leidhin et al., 2025).

Children undergoing CT imaging are exposed to high radiation doses, which can increase with repeat scans often needed for insufficient diagnostic clarity or long-term monitoring. The most prevalent conditions requiring three or more CT scans include trauma (23.2%), hydrocephalus (5.3%), and brain tumors (1.4%). The head is the most commonly imaged area, particularly for diagnosing convulsions and assessing traumatic brain injuries. Concerns about the cumulative radiation dose are significant, as children's increased sensitivity and longer lifespans heighten their risk for long-term effects (Yoshitake et al., 2020).

2.4.1 Hydrocephalus

One of the most common neurological abnormalities seen in pediatric imaging is hydrocephalus, which is characterized by an abnormal buildup of cerebrospinal fluid (CSF) in the cerebral ventricles, which causes ventricular expansion and elevated pressure inside the skull. Because of their quick acquisition, accessibility, and high sensitivity in displaying ventricular size and configuration, brain CT scans are essential for the timely diagnosis and continued treatment of hydrocephalus. Periventricular lucency and transependymal CSF flow are two indicators of elevated pressure that CT is especially helpful in detecting. It also makes it possible to evaluate open fontanelles and suture separation in newborns and infants (Robson et al., 2017).

When no clinical intervention has been performed, repeat CT imaging is often necessary if there is a progressive increase in head circumference, a bulging fontanelle, irritability, or vomiting. Additionally, follow-up CT scans are essential after surgical procedures to evaluate the function and patency of ventricular shunts, detect blockages or over-drainage, and determine if revision surgery is required (Robson et al., 2017).

2.4.2 Subdural Effusions

It is fluid buildups that occur in the space just beneath the dura mater, the outer layer covering the brain. They often happen in children due to conditions like bleeding disorders, infections such as meningitis, or head injuries. On a CT scan, these effusions show up as areas that look less dense than the brain tissue, located outside the brain itself (Kumar et al., 2008).

In infants who still have open sutures in their skulls, these growing fluid collections can cause noticeable head enlargement and even slow down their developmental progress. CT scans play an important role in detecting these effusions early, assessing their size and the pressure they may be putting on the brain, and spotting any serious complications like brain herniation or a shift in the brain's midline (Kumar et al., 2008).

For children who come in with symptoms like seizures, confusion, or unexplained increases in head size, CT imaging is a critical tool to understand what's going on. If surgery isn't immediately needed and doctors decide on a more conservative approach, regular follow-up CT scans help track any changes in the size or character of the effusion to guide ongoing care (Kumar et al., 2008).

2.4.3 Intracranial Cysts

It's a fluid-filled cavity that can arise naturally or from trauma or infection, including arachnoid, porencephalic, and neuroglial cysts. These cysts may be asymptomatic in children or cause issues such as seizures, macrocephaly, or delayed brain development (Daley et al., 2021).

High-resolution CT scans are useful for distinguishing these cystic lesions from solid brain masses by examining their shape and density. For instance, a porencephalic cyst typically appears as a clearly defined, low-density area that might connect with the subarachnoid space or brain ventricles. CT scans also play an important role in surgical planning and in assessing how the cyst affects nearby brain tissue (Daley et al., 2021).

Although MRI offers superior soft-tissue contrast, CT remains the preferred modality in acute or critical situations. Repeat CT imaging may be necessary if the cyst enlarges, symptoms worsen, or further surgical assessment is needed (Daley et al., 2021).

2.4.4 Macrocrania (Enlarged Head Circumference)

Subdural effusions and intracranial cysts can lead to macrocrania, which is accurately assessed using CT scans. Macrocrania is characterized by a head circumference that

surpasses the 97th percentile for age and sex, potentially indicating various intracranial abnormalities. Both benign familial characteristics and serious conditions like space-occupying lesions, hydrocephalus, or subdural collections can cause macrocrania in newborns and infants (Haws et al., 2017).

CT can provide rapid evaluation of the skull, ventricular system, brain parenchyma, and extra-axial fluid spaces, which assists in differentiating between conditions such as benign enlargement of the subarachnoid spaces and subdural fluid collections in infants presenting with macrocephaly. However, because pediatric patients are more sensitive to ionizing radiation, the use of CT should be carefully justified, particularly when repeated imaging is required for follow-up. In many cases, ultrasound or MRI may be considered as alternative modalities when appropriate, especially in infants with open fontanelles or when repeated evaluation is necessary (Haws et al., 2017).

2.4.5 Megalocephaly (Enlarged Brain)

Macrocephaly often occurs due to megalcephaly, which means an unusually large volume of the brain's cortex and white matter. This condition can be associated with genetic disorders such as PTEN mutations, metabolic problems, or developmental issues. CT scans help distinguish megalcephaly from hydrocephalus by showing an increased brain size without any compression of the ventricles or shift of the brain's midline. Unlike hydrocephalus, megalcephaly does not involve a blockage of cerebrospinal fluid (CSF) (Momodu et al., 2024).

Most people with megalcephaly do not show symptoms and are diagnosed by chance. However, some may experience seizures, developmental delays, or traits related to autism. CT scans are typically used to diagnose this condition. Because of concerns about radiation

exposure, repeat imaging is generally avoided in children who don't show symptoms, but is advised for those who do or when further evaluation is needed (Momodu et al., 2024).

In addition to its primary role in diagnosing conditions like hydrocephalus, macrocrania, and intracranial cysts, CT scans also play a supplementary role in evaluating seizure disorders, head trauma, infections, stroke-like syndromes, and intraventricular hemorrhage in neonates (Momodu et al., 2024).

According to the ALARA principle, pediatric CT protocols are made to minimize radiation exposure and maximize image quality to protect young patients' developing tissues. Despite the advantages of CT over plain radiography in paranasal sinus diagnosis, it presents some disadvantages, primarily due to radiation exposure to radiosensitive organs within the scanning field, such as the thyroid gland and the eye lenses, which are susceptible to radiation-induced cataracts. Therefore, it is crucial to avoid this inherent detriment during cranial CT examinations (Valentin, 2007).

While CT scans are essential for accurate diagnosis, they also carry a risk of radiation exposure, especially with repeated exams, which can increase the likelihood of radiation-induced conditions such as cancer. Hence, it is vital to balance the benefits of CT imaging against the potential radiation exposure risks. Ongoing efforts to reduce radiation dose without compromising diagnostic quality include advances in CT technology, dose optimization strategies, and strict adherence to safety guidelines (Brenner & Hall, 2007; Icrp, 2007).

The significantly higher utilization of CT has raised concerns about the possible risk of cancer induction from the radiation dose during CT exams. Many agree that patients should receive radiation doses ALARA, despite the fact that the existence of such a risk is

still debatable regarding the level of radiation doses usually received in diagnostic CT (Brenner & Hall, 2007).

Radiation dose will be decreased by choosing the appropriate scan volume and adjusting scan parameters like pitch, kVp, mAs, rotation time, slice width, slice gap, and the use of dose modulation techniques. However, the major disadvantage of the use of “automatic tube current modulation” for CT brain is the decreased image quality due to asymmetry in head shape when compared to other body parts, but it would be acceptable to use “automatic tube current modulation” provided diagnostic image quality is maintained (Smith et al., 2008).

Motivated by public interest, the Society for Pediatric Radiology has organized a multidisciplinary conference to address concerns about exposure to CT radiation in children (Society of Pediatric Radiology, 2002), which was developed in the 1960s by the Atomic Energy Commission (the predecessor of the Nuclear Regulatory Commission) and the Department of Energy, was powerfully incorporated as a unifying concept for pediatric CT dose reduction efforts (United States Nuclear Regulatory Commission, 2011).

In late 2002, there were still relatively few established guidelines for performing CT scans in children. Up to that point, little emphasis had been placed on adjusting scanning parameters such as beam energy (kVp), tube current (mA), and pitch based on the child's size, known as size-based scanning (Frush et al., 2002). By the end of 2003, the study pointed out that despite the growing use of CT and increased awareness, there had not been a corresponding improvement in understanding the risks or in applying techniques to reduce those risks (Frush et al., 2003).

2.5 Radiation Dose Measurement in Computed Tomography

Evaluating and managing radiation dose in CT is an essential part of safe radiology practice. Unlike conventional X-ray imaging, where the dose estimated easily, CT's rotational

and cross-sectional nature makes dose measurement more difficult. As a result, standardized dose indices developed for display on CT scanner consoles, enabling operators to monitor and optimize protocols. The Volume CT Dose Index (CTDI_{vol}) and the Dose-Length Product (DLP) are the two most well-known indices (McCollough et al., 2011).

The significant advancement brought about by computed tomography (CT) in medical diagnosis, as previously discussed, has led to its widespread use. Consequently, a large number of people have become aware of the associated radiation exposure. To minimize these risks and ensure the safe and continued use of this effective diagnostic tool, it is essential to accurately measure and understand CT dose parameters, as they are directly related to the parameters used in imaging protocols (Edyvean et al., 2012).

Therefore, to effectively manage and reduce radiation exposure in clinical practice, it is crucial to comprehend the fundamental dose descriptors applied in both clinical and research CT settings. These descriptors define the amount of radiation delivered to the patient and provide a basis for comparison and protocol optimization (Edyvean et al., 2012).

2.5.1 Radiation Dose Metrics in CT

Computed tomography dose metrics and computations describe the procedures and figures used to measure and evaluate the radiation exposure a patient experiences during a CT scan. In CT imaging, X-rays used to produce finely detailed cross-sectional pictures of the body. CT scans are useful for diagnosis, but in order to reduce any risks to the patient, it's critical to control and monitor the radiation dosage (Tootell, 2018).

In pediatric brain CT, accurate dose assessment is necessary to balance diagnostic quality with patient safety. Children's unique anatomical and physiological characteristics require customized evaluations that consider their increased organ sensitivity and smaller size compared to adults. Traditional metrics like the computed tomography dose index (CTDI) and dose-length product (DLP) should be interpreted carefully, as children's brains absorb radiation differently than adults, affecting the overall dose received (Tootell, 2018)

Because CT scans expose patients to radiation from all directions, the radiation dose distributed more evenly. The X-ray fan beam, the shaped filter, and patient axis spacing all affect the distribution. The volume computed tomography dose index (CTDIvol) measured in (mGy) describes the absorbed dose, while the dose-length product (DLP) reflects the total radiation dose over the length of the examination. The effective dose, measured in Sieverts (Sv), estimates the cancer risk associated with radiation exposure (Edyvean et al., 2012).

Advancements in technology, such as photon-counting detector CT (PCD-CT), have shown promise in enhancing image quality while reducing radiation exposure, thereby improving safety in pediatric imaging. Additionally, individual patient anatomy plays a significant role; studies have demonstrated that factors like weight and age influence the absorbed dose, highlighting the necessity for patient-specific imaging protocols (McCollough et al., 2011).

2.5.1.1 Computed Tomography Dose Index (CTDI)

The standardized Computed Tomography Dose Index (CTDIvol) represents the average absorbed dose within the scanned volume of a CT examination. It is commonly shown on the CT scanner console and is measured in milligrays (mGy). The CTDIw (weighted CTDI), which takes into consideration the pitch factor and the non-uniform dose distribution throughout the scan field, is the source of the CTDIvol. A higher CTDIvol means that the patient exposed to a greater radiation dose. Tube voltage (kVp), tube current-time product (mAs), beam collimation, and scanner geometry are some of the variables that affect CTDIvol. It is a useful metric for comparing the radiation output of various CT scanners and protocols, but it ignores the patient's body size and scan duration (Tootell, 2018).

CTDIvol measures the average radiation dose over a predetermined body length or scan segment in a defined phantom, which is a standardized model that mimics the human body,

like polymethylmethacrylate (PMMA), acrylic, Perspex, or Lucite with a standard size of 14 cm length and 16 and 32 cm diameter, representing head and body, respectively, as shown in (Fig. 2.1) (AAPM, 2008). This metric considers the radiation exposure duration and intensity during the CT scan (Edyvean et al., 2012).



Figure 2.1: CTDI PMMA phantoms of standard size, with an axial length of 14 cm. diameters: 16 head and 32 cm body, with an electrometer and ion chamber measuring 100 mm (Edyvean et al., 2012).

The CTDI, which is determined using the dose integral over a given length, is calculated using this formula (Edyvean et al., 2012):

$$CTDI_{vol} = \frac{1}{n} \sum_{i=1}^n CTDI_{air,i}$$

Where: n is the number of measurement points along the scan length.

CTDI air is the CTDI calculated at each point in a cylindrical phantom filled with air (Tootell, 2018).

Weighted CTDI, or CTDI_w, accounts for the various tissue densities found in the body. It reflects the attenuation properties of different tissues by using a weighted average of the

CTDI values in various phantom regions. The following is the formula for CTDI_w (Edyvean et al., 2012):

$$CTDI_w = \frac{1}{3}CTDI_{head} + \frac{2}{3}CTDI_{body}$$

Where: CTDI head is the CTDI calculated in the head region of the phantom. CTDI body is the CTDI calculated in the body region of the phantom.

CTDI_{vol} is also computed as follows to take into consideration non-contiguous slices or varying pitch values (Edyvean et al., 2012):

$$CTDI_{vol} = CTDI_{weighting} / Pitch.$$

The American Association of Physicists in Medicine has created size-specific dose estimates (SSDE) to normalize CTDI_{vol} based on patient diameter in order to take patient size variations into consideration (AAPM, 2011). Therefore, CTDI_{vol} is crucial for assessing radiation exposure during CT scans, which aids in protocol optimization and patient safety.

2.5.1.2 The Dose Length Product (DLP)

The entire amount of radiation energy given to the patient during a CT scan is measured by the Dose Length Product (DLP), which is measured in milligray-centimeters (mGy·cm) and is computed by multiplying the CTDI_{vol} by the scan length (L) (DLP=CTDI_{vol} × Scan length) as shown in (Figure 2.2) (Edyvean et al., 2012).

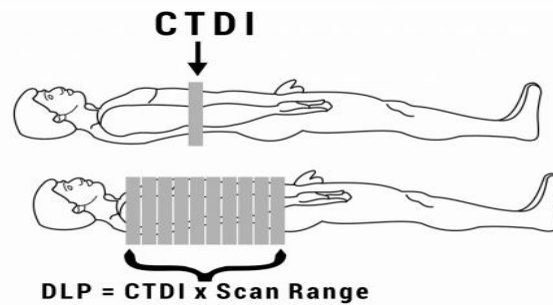
Even though DLP provides a more accurate picture of the total exposure, patient-specific variables like age, body habitus, and organ radiosensitivity still not directly taken into consideration. While the CTDI_{vol} used to compare the absorbed dose for particular protocols, the DLP used to calculate the radiation risk because it considers every aspect of

the protocol. And because phantom and patient anatomy differ, CTDI and DLP metrics are not intended to accurately estimate the radiation dose absorbed by specific patients, even though they are standardized indices for radiation dose (McNitt-Gray, 2002).

Figure 2.2: The difference between CTDIvol and DLP that considers the patient's scan length (Huda, 2013).

2.5.1.3 The Effective Dose

The Effective Dose (ED) is a calculated value that reflects the overall risk of radiation-induced cancer or hereditary effects. Using tissue-weighting factors that take into



consideration the different radiosensitivity of various organs and tissues, it expressed in a unit known as Sieverts (Sv). Anthropomorphic phantom measurements or numerical simulations using the Monte Carlo technique can be used to estimate doses effectively, but they require specific knowledge (Tootell, 2018). DLP, which frequently reported by clinical CT systems, can used to estimate the effective dose using a methodology proposed by the European Working Group. One way to describe the relationship is:

$$ED = k \cdot DLP$$

Where the conversion coefficient denoted by (k), it depends on the anatomical region scanned and ideally the patient's size and age. Typically employed (k)-factors for various parts of the body are provided by the NRPB (AAPM, 2008), with distinct values for adults and children depending on varying phantom sizes.

When comparing radiation risks from various imaging modalities and evaluating radiation exposure at the population level, effective dose is a helpful metric. It is crucial to remember that an effective dose is a risk assessment rather than a measurement of absorbed dose. In short, radiation dose measurement in CT can be illustrated by a simple diagram that is shown in Figure 2.3 (Nett, 2019).

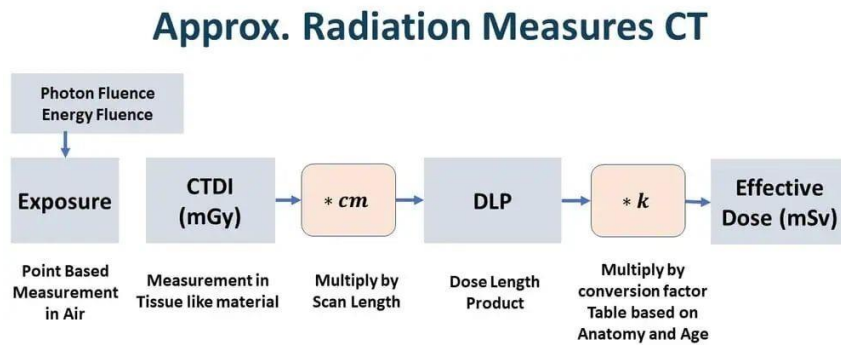


Figure 2.3: Simple measurement of effective dose in CT (Nett, 2019).

2.5.1.4 Limitations of CTDIvol

Although CTDI_{vol} and DLP are crucial dose descriptors in CT imaging, it is important to be aware of their important limitations. CTDI_{vol} is not the same as the patient's actual dose; it represents the average dose measured in a PMMA phantom. It makes the rarely found assumption that the patient is the same size and shape as the phantom. Wide beam configurations may also make it more difficult to measure and interpret CTDI_{vol} (McCollough et al., 2011).

Scanned Length more than 100 mm may underestimate the dose because scatter tails cause the average dose to the central slice to increase with longer scan lengths. Additionally, CTDI₁₀₀ overestimates doses for scans that are shorter. Also, since the phantom and chamber

lengths were intended to be longer than the beam width, the development of wide beam scanners has resulted in an issue with the CTDI as a radiation dose metric (Edyvean et al., 2012). This has led to a mistake called the "CTDI efficiency." The short phantom and chamber length affect the current CTDI₁₀₀ efficiency, as shown in Figure 2.4.

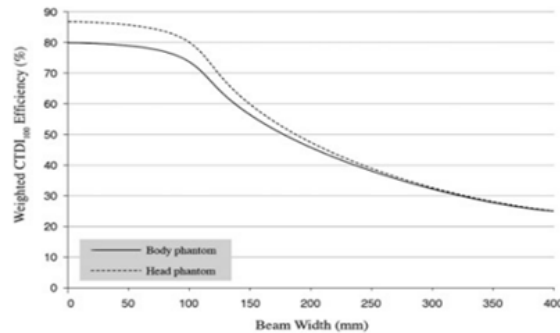


Figure 2.4: CTDI efficiency as a function of beam width (Edyvean et al., 2012).

The patient size variability also has an impact on the CTDI_{vol} value; it will be the same for two patients of different sizes scanned using the same protocol, but the actual absorbed doses will differ because CTDI_{vol} is based on specific phantom sizes (AAPM, 2011). Image noise may be higher, and the dose per unit mass may be lower for larger patients. For pediatric patients in particular, this disparity is significant.

Because the CTDI_{vol} is measured using standard phantoms, which might not accurately reflect patient anatomy, it is not indicative of actual patient doses for scan lengths shorter than 100 mm. It is still a helpful tool for comparing protocol doses and improving clinical procedures, though.

2.6 Image Quality versus Radiation Dose: A Delicate Balance

In CT imaging, radiation dose and image quality closely linked, with improvements in one often affecting the other. Obtaining an image that is of adequate diagnostic quality to enable the doctor to make a correct diagnosis while utilizing the smallest possible radiation

dose that is reasonably achievable is the most important objective of any radiological examination (World Health Organization, 2016). Dealing with children makes this delicate balance, which is the foundation of radiation protection procedures, even more important and sensitive.

Many technologies have developed to reduce radiation exposure. Still, there is a requirement to optimize and adjust scan parameters. However, we must also remember that lowering the dose can increase image noise and reduce image quality. As the quality of the image in CT is primarily dependent on the X-ray detected, technical factors in pediatric CT can be reduced because children have less thickness and density of bones (Tack et al., 2012).

The clarity of the image depicting the anatomy in CT is dependent on a number of physical factors. The radiation dose has varying effects on these factors, which include the following:

- Noise: The random distribution of X-ray photons that reach the detector is what causes the noise in CT images. When the dose is low, image noise increases, making small details harder to see. In pediatric imaging, lowering the dose is essential for the child's safety, but this frequently leads to increased noise. Iterative reconstruction is one of the unique image processing techniques used by modern CT scanners to reduce noise without significantly raising dose (Tack et al., 2012).
- Low-contrast resolution: The ability of the CT scan to differentiate between tissues with similar densities, the brain is gray and white matter known as low-contrast resolution. Lowering the dose can make it more difficult to detect these subtle differences because high noise can make it difficult to do so (Tack et al., 2012).
- Spatial resolution: The clarity of small objects or fine details on a CT scan referred to as spatial resolution. Small anomalies, such as microscopic tumors or fractures, found with the aid of high spatial resolution. A higher dosage might be required to maintain

the image's clarity, though, as the use of thin slices and sharp image reconstruction techniques frequently increases noise. In order to minimize radiation risk and maintain a low dose, physicians may be willing to accept a slightly lower resolution in pediatric imaging (Tack et al., 2012).

- **Artifacts:** Parts of the CT scan that do not accurately depict the anatomy known as artifacts, and they brought on by physical effects, metal objects, or patient movement. Certain artifacts, like motion artifacts, may worsen or be more difficult to fix at low dosages. Sometimes these issues can be lessened by using sedation, a slightly higher dose, or faster scanning (Tack et al., 2012).

2.7 Methods for Evaluating and Managing CT Doses

A combination of proactive management techniques and strong assessment methodologies is required for the effective management of CT radiation dose. These methods seek to minimize patient exposure while maintaining the quality of diagnostic images (McCollough et al., 2011).

2.7.1 Dose Reference Levels (DRLs)

DRLs are a useful and efficient tool for controlling patient doses in medical imaging, and their concept has emerged in the ongoing quest to optimize radiation protection. Since its initial introduction by the International Commission on Radiological Protection (ICRP) in 1990, this idea has been embraced and expanded upon by regulatory agencies and health organizations all over the world (Vaño et al., 2017).

2.7.1.1 Definition and Purpose of DRLs

A DRL is not a threshold for safe or unsafe behavior, nor is it a dose limit that must never be exceeded. Rather, a DRL is an investigational level that is used to determine when a patient or group of patients is receiving an abnormally high radiation dose for a particular diagnostic procedure. According to (Picone et al., 2025), the DRL value is usually set at the 75th percentile of the dose distribution gathered from a comprehensive survey of current clinical practices in a particular geographic area (a hospital, region, or nation).

The main purpose of DRLs is to promote optimization. If a department finds that its doses regularly exceed the DRL, this should trigger a review and investigation. When high doses are found, departments should review their procedures, methods, and equipment to identify the cause and make corrections. Without sacrificing the quality of diagnostic images, DRLs contribute to the reduction of unnecessary dose variations across hospitals and the enhancement of overall practice standards through this iterative process of measurement, comparison, and improvement (Picone et al., 2025).

2.7.1.2 Development of DRLs for Children

Setting and applying DRLs in children is more complex than in adults, but also more important. A single DRL cannot be used for all children because newborns and adolescents have very different body sizes. As a result, pediatric DRLs need to be divided into several groups, usually according to weight or age (e.g., <1 year, 1-5 years, 5-10 years, and 10-15 years). Age-group-specific guidelines for routine pediatric head CT are recommended by the American Association of Physicists in Medicine (AAPM, 2015).

Worldwide, a lot of work has been done to set up local and national DRLs for pediatric brain CT exams. For instance, a study conducted in Jordan surveyed seven hospitals and suggested national DRLs for pediatric head scans. For the 1–5 year age group, the DLP was 680 mGy•cm, and the 75th percentile CTDI_{vol} was 39 mGy (Rawashdeh et al., 2019). In 2008, age-based reference levels for radiation doses in children were established in Switzerland. The typical DLP values ranged from 350 mGy•cm for babies under one year old to 780 mGy•cm for children aged 10 to 15 years (Verdun et al., 2008).

Ongoing improvements at the largest children's hospital in Greece have led to local radiation dose levels that are lower than many of the European benchmarks reported in other studies (Ploussi et al., 2020). A recent nationwide dose audit in the UK produced thorough data for pediatric DRLs and a current standard by which to measure them (Worrall et al., 2022). A single-hospital study conducted in Abu Dhabi, United Arab Emirates, emphasized the significance of ongoing dose monitoring and comparison with global standards (Abulail et al., 2023).

There is a great deal of variation in dose practices around the world, as these and other studies. This highlights the importance of establishing local DRLs. Local DRLs are more effective for optimizing radiation doses because they better reflect the specific equipment, techniques, and clinical practices used in each hospital or region, unlike national or international DRLs that may not always fit local circumstances (Sabarna & Rumman, 2017).

2.7.2 Automatic Exposure Control (AEC)

AEC systems advanced features built into modern CT scanners that adjust the X-ray mAs automatically during a scan. Their goal is to keep image quality consistent while minimizing the radiation dose to the patient. AEC works by changing the amount of radiation based on how much the patient's body absorbs it. Thinner or less dense areas receive less radiation, while thicker or denser areas get more. This patient-specific adjustment helps optimize and reduce the overall dose. Although different manufacturers use various algorithms, the primary aim is always the same to produce the best possible images with the lowest radiation exposure (Tack et al., 2012).

ATCM considered one of the most significant developments in dose reduction. These intelligent systems continuously modify the tube current in real-time based on the patient's attenuation, rather than employing a fixed mAs value during the scan. There are two primary

categories of modulation: z-axis modulation and Rotational (or angular) modulation (Lee et al., 2008).

The Z-axis modulation adjusts the tube current as the scanning table moves along the patient's body length. For example, when scanning the chest, the system uses a lower mAs over the lungs (which are less dense) and a higher mAs near the shoulders (which are denser). Rotational (or angular) modulation changes the tube current as the X-ray tube rotates around the patient. For instance, in an abdominal scan, the body absorbs less radiation from front to back (anterior-posterior direction) than from side to side (lateral direction). The system reduces the current where attenuation is low and increases it where attenuation is higher, balancing dose and image quality (Lee et al., 2008).

Today, ATCM systems regarded as a standard feature in contemporary CT scanners and greatly reduce excess dose while standardizing image quality across various body parts.

2.7.3 Iterative Reconstruction (IR) Techniques

Iterative Reconstruction (IR) algorithms are a big step forward in CT image reconstruction. Unlike traditional filtered back projection (FBP) methods, which require higher radiation doses to produce clear images due to their sensitivity to noise at low doses, IR significantly reduces noise and artifacts while maintaining image quality. IR achieves this by using advanced physical and statistical models repeatedly refine the image. It starts by creating an initial image, compares it to the original raw data to identify differences caused by noise. Through multiple cycles of correction, the algorithm gradually improves the image, producing a clearer result with much less noise and lower radiation exposure (Tack et al., 2012).

This approach allows for lower mAs settings, which directly lowers the dose to the patient, sometimes by 30–50% or more, depending on the specific IR algorithm and clinical use. As a result, IR techniques have become an essential part of modern CT dose optimization, enabling radiologists to obtain high-quality diagnostic images while minimizing radiation exposure (Edyvean et al., 2012).

2.7.4 Optimization of Patient-Specific Protocols

For the best dose management, CT scan settings in standard protocols should be adjusted for each patient's unique needs, not just rely on general dose reduction technologies. Such as the patient's age, height, weight, the reason for the scan, and which part of the body scanned (Tack et al., 2012).

This is especially important for children since their bodies are smaller and they are more sensitive to radiation. Pediatric scans usually use lower energy and lower radiation levels, and the scan length kept as short as possible to reduce exposure. For adults, adjusting the settings based on body size, like using less radiation for smaller patients, can also make a big difference in lowering the dose without affecting image quality (Parakh et al., 2016).

The goal of patient-specific protocol optimization is to use the least amount of radiation required to accomplish the diagnostic goal while closely following the ALARA principle is the aim of patient-specific protocol optimization (AAPM, 2011).

2.7.5 Dose Monitoring and Management Systems

Advanced dose monitoring and management systems (DMMS) employed in many imaging centers to effectively monitor and manage patient radiation exposure. These systems

facilitate not only real-time monitoring but also retrospective analysis and the identification of high-dose outliers because they accumulate dose data automatically from CT scanners.

DMMS is able to monitor trends in dose usage, generate incidental and cumulative patient dose reports, and facilitate quality assurance initiatives. By delivering comprehensive radiation exposure information, these systems allow radiology departments to identify opportunities for improvement, implement targeted dose reduction practices, and ensure compliance with regulations. Further knowledge about radiation exposure on the population level and long-term effects of CT imaging may potentially be addressed with research using data collected in DMMS (Tsalafoutas et al., 2020).

2.7.6 Photon-counting Computed Tomography (PCCT)

Recent technological advances in CT have introduced PCD-CT, a novel imaging technology that has the potential to significantly improve pediatric brain imaging. Unlike conventional CT systems that rely on energy-integrating detectors, PCD-CT directly counts individual X-ray photons and measures their energy. This approach improves spatial resolution and reduces electronic noise, allowing clearer visualization of small anatomical brain structures that are important for accurate pediatric diagnosis (Horst et al., 2025).

An important advantage of PCD-CT is its higher dose efficiency, which enables the production of high-quality images while using lower radiation doses compared with conventional CT systems. This feature is particularly valuable in pediatric imaging, where minimizing radiation exposure is essential due to the increased radiosensitivity of children and the potential need for repeated follow-up scans. Therefore, PCD-CT represents a promising advancement for improving diagnostic performance while supporting radiation dose optimization in pediatric neuroimaging (Horst et al., 2025).

2.8 CT Dose Optimization Challenges

Some obstacles still stand in the way of attaining the ideal radiation dose reduction while preserving the quality of diagnostic images, even with notable developments in CT technology and dose management techniques. These difficulties are complex, involving organizational, clinical, and technological elements (Tack et al., 2012).

2.8.1 Clinical Practice variation

The way CT scans are carried out varies greatly, not only between hospitals but sometimes also within the same organization. Because of these variations, individuals may receive varying doses of radiation for virtually the same kind of scan. This happens due to several causes, including inconsistent protocols, variations in CT scanner models or software, radiologists' personal preferences, and technologists' differing levels of experience or training (Tack et al., 2012).

To overcome this obstacle, strong quality assurance programs must put in place, all staff members involved in CT imaging must receive ongoing education and training, and standardized, evidence-based protocols that routinely reviewed and updated must create. Dose management systems, which offer data-driven insights into dose trends and protocol adherence as mentioned before, can be used to detect and lessen this variability (Tack et al., 2012).

2.8.2 Keeping Dose and Image Quality in Check

One of the biggest challenges in CT dose optimization is finding the right balance between radiation dose and image quality. When the radiation dose reduced, image noise often increases, which can hide subtle abnormalities and make diagnosis more difficult. This problem has significantly reduced by iterative reconstruction techniques, but it is still

challenging to make the ideal balance between the lowest dose and diagnostically acceptable image quality.

This balance is somewhat subjective because it frequently affected by the radiologist's preferences and experience, the particular anatomical region scanned, and the clinical question being addressed. It is crucial to establish precise, evidence-based standards for acceptable image quality at lower dosages, but doing so will require close cooperation and agreement from radiologists, medical physicists, and other key participants (Picone et al., 2025).

2.8.3 Patient Size and Body Habitus

The size and body composition of the patient have a significant impact on how much radiation needed to create high-quality diagnostic images. Larger patients typically require higher radiation doses to obtain sufficient image quality because they attenuate more of the X-ray beam. Despite the fact that AEC systems made to modify dosage according to patient size, their effectiveness varies, and manual adjustments are sometimes still required (Strauss, 2014).

For pediatric patients or those with unusual body shapes, choosing the right scanning protocol and precisely estimating patient size can be especially difficult. Poor image quality or excessive radiation exposure can arise from selecting the wrong protocol, whether it be by overestimating or underestimating the patient's size. And that's why the goal of ongoing research is to create increasingly sophisticated, patient-specific dose modulation methods that can precisely adjust radiation output to the anatomy of each individual patient (Strauss, 2014).

2.8.4 Insufficient Knowledge and Instruction

Some healthcare professionals, such as referring physicians, radiologists, and technologists, may still lack a thorough understanding of radiation risks and dose optimization principles despite growing awareness campaigns. The radiation dose linked to various imaging modalities and referring physicians may not always know the existence of lower-dose substitutes. Because of worries about image quality, radiologists and technologists might not be making the most of all the dose reduction features on their CT scanners or might be reluctant to stray from accepted, higher-dose protocols (Alyousef et al., 2023).

To overcome this obstacle, it is necessary to implement continuous education and training programs, encourage interdisciplinary cooperation, and cultivate a culture of radiation safety in order to guarantee that the right imaging tests are requested and carried out at the lowest feasible dose (Alyousef et al., 2023).

2.8.5 Economic and Regulatory Pressures

CT dose optimization may also be hampered by financial constraints and regulatory requirements. Although the goal of regulations is to protect patients, they may not always be in line with the most recent developments in technology or occasionally be seen as onerous. Higher-dose protocols may unintentionally be used because of financial constraints, such as the requirement to optimize patient throughput or reduce scan times. For some institutions, the expense of introducing complete dose management systems or replacing outdated CT scanners with cutting-edge dose reduction technologies may also be a deterrent (Tsapaki, 2020).

Careful planning and strategic investment in dose optimization initiatives are necessary to strike a balance between the need for patient safety, economic realities, and regulatory compliance (Tsapaki, 2020).

2.8.6 Monitoring Cumulative Doses

It is still very difficult to track the total radiation dose for a single patient, particularly for those receiving several CT scans from various medical professionals. A centralized, interoperable system for tracking patient doses across various facilities is frequently absent, even though dose management systems can track doses within a single institution. This makes it challenging to determine a patient's lifetime radiation exposure and to decide on appropriate imaging tests in the future. To address this issue and provide a more complete picture of patient radiation exposure, it is imperative to create national or regional dose registries and encourage interoperability among various dose tracking systems (Tsapaki, 2020).

2.9 Principles of CT Dose Optimization

CT dose optimization is a continuous process aimed at achieving the lowest possible radiation dose while maintaining the diagnostic quality of the images. This principle, often summarized by the acronym ALARA, is a cornerstone of radiation protection in medical imaging. Achieving ALARA in CT involves a multifaceted approach that considers technical parameters, patient factors, and clinical indications (Seeram, 2023).

2.9.1 Estimating Cancer Risk from CT

Several comprehensive epidemiological studies have attempted to quantify the level of risk. One of the most well-known of these, conducted in the UK and published in The Lancet,

followed a large number of children and adolescents who underwent CT scans. There is a clear dose-response relationship between cumulative radiation exposure to the brain and the subsequent risk of brain cancer and leukemia. The study found that a cumulative dose of 50–60 mGy might triple the risk of brain cancer (Pearce et al., 2012).

Another comprehensive study conducted in the US and published in *JAMA Pediatrics* estimates that the annual CT scans performed in the US may cause an additional 4,870 cancers in the future. The study found that 43% of these cases could be saved by reducing dosages to the lowest quartile of current practices (Miglioretti et al., 2013).

It is important to put these risks in context. With just one CT scan, a person's absolute risk of developing cancer is still extremely low. However, when an examination is not medically justified or when a higher-than-necessary dose is given, this small risk becomes unacceptable. And this is raised up with the repeated examination situation, where doses accumulate over time and increase the cumulative lifetime risk (Sheppard et al., 2018).

This is the exact focus of this thesis because safer follow-up strategies depend on assessing and comprehending the doses in patients who need frequent follow-ups (such as patients with hydrocephalus, tumors, or following severe trauma).

2.9.2 Justification and Optimization

Given these risks, the justification principle becomes the most important radiation safety precaution. Before sending a child for a CT scan, the referring physician must ask himself these questions: Is this examination truly necessary? Do findings change the management plan? In addition, is there an alternative non-ionizing radiation diagnostic method, such as ultrasound or magnetic resonance imaging (MRI)? (Brady et al., 2012). The

examination can only be justified if the anticipated clinical benefit clearly outweighs the possible radiation risks.

The International Commission on Radiological Protection (ICRP) states that justification and optimization are two crucial rules for medical exposure. Justification ensures that the benefits of a CT scan exceed the radiation exposure risk to the patient. Careful consideration must give to the clinical question, alternative imaging modalities, and the potential impact of the CT scan on patient management. On the other hand, optimization seeks to ensure that the CT scan performed with the least amount of radiation necessary to achieve the diagnostic objective, when necessary. This means implementing technologies for dose reduction, selecting appropriate procedures, and modifying parameters to meet each patient's needs (Seeram, 2023).

2.10 Technical Factors Affecting Dosage

The radiation dose administered during a CT scan is directly influenced by a number of technical factors. For dose optimization, it is essential to comprehend and suitably modify these parameters.

The radiation dose directly regulated by the Tube Current-Time Product (mAs) setting, which also affects the quantity of X-ray photons generated. Although the dose greatly reduced by lowering mAs, image noise is increased. Systems that use AEC dynamically modify mAs throughout the scan to minimize dose and preserve a constant image quality (Romans, 2025).

kVp is the potential difference between the X-ray tube's cathode and anode that propels electrons across the tube. It mostly influences the energy (quality) of the electrons and, to a lesser degree, their number. Reducing the kVp lowers the X-ray beam's energy, which lowers

the dose given to the patient. For instance, lowering the voltage from 120 kVp to 100 kVp will decrease the dose by 30 to 40%, and lowering it to 80 kVp can eliminate the dose by up to 65%. However, it can also decrease image contrast, especially for iodine-based contrast agents, and increase image noise (Nagayama et al., 2018).

To optimize kVp settings according to patient size and clinical indication, modern CT scanners frequently use automated kVp selection or permit dual-energy imaging, and this works very well, especially for small children and for CT Angiography scans that use iodinated contrast material, because the lower X-ray energy makes iodine stand out more (Nagayama et al., 2018).

The ratio of table movement per rotation to beam collimation is known as pitch in helical CT. Increasing the pitch factor can shorten the scan time and reduce the radiation dose to the patient. However, this often comes at the cost of image quality, particularly when evaluating small lesions or regions with complex anatomy. Selecting the appropriate pitch is therefore crucial to achieving the right balance between minimizing radiation exposure and maintaining sufficient image detail for accurate diagnosis (Tack et al., 2012).

Narrower beam collimation and thinner slices generally yield higher image resolution, but oversampling can raise the dose. Conversely, wider collimation and thicker slices reduce dose but may compromise spatial resolution. Selecting the ideal slice thickness is essential for dose optimization and diagnostic precision (Tack et al., 2012).

As previously indicated, iterative reconstruction (IR) algorithms are essential for optimizing CT dose because they enable lower mAs settings while successfully lowering image noise. Choosing the best IR technique allows for the creation of diagnostic images at

significantly lower dosages than with conventional filtered back projection techniques (Nagayama et al., 2018).

Accurate patient centering is essential for minimizing radiation exposure while maintaining image quality. Even a small misalignment, for example, just 3 cm or 6 cm off-center, can increase the radiation dose by approximately 18% and 41%, respectively. Improper centering can also raise surface and peripheral doses, especially when AEC systems are in use, as they may compensate incorrectly for the patient's position. Ensuring precise alignment within the scanner's isocenter is therefore critical for achieving optimal diagnostic quality with the lowest possible dose and minimal image noise (Yang, 2020).

Only the anatomical region of interest should be included in the scanned area. For example, when scanning the brain, extending the scan length by even a few centimeters can raise the total radiation dose (DLP) and unnecessarily expose sensitive organs to radiation, like the thyroid gland or the eye lenses. Therefore, to prevent excessive exposure and to guarantee patient safety, careful planning and accurate scan range selection are crucial (McCollough et al., 2011).

2.11 Role of Phantoms and Dosimetry in CT Dose Measurement

Phantoms are physical replicas made to resemble human body parts and tissues, enabling precise and regulated dosage testing. The use of cylindrical acrylic phantoms, with smaller ones (about 16 cm) representing the head and larger ones (about 32 cm) representing the body, is a typical example. These phantoms aid in the precise measurement of CT dose index volume (CTDI_{vol}) (Goldman, 2007).

Dosimetry techniques use specially designed detectors to measure radiation dose. Ionization chambers commonly used for CTDI measurements because they provide an accurate assessment of the absorbed dose. Additional uses for thermoluminescent dosimeters (TLDs) and optically stimulated luminescent dosimeters (OSLDs) include patient dose monitoring. Because they ensure precise CT scanner calibration and the

effectiveness of dose reduction strategies, these tools are essential for research, protocol optimization, and quality assurance (Goldman, 2007).

2.12 Role of Artificial Intelligence in CT Radiation Dose Optimization

CT is integral to contemporary clinical practice but significantly contributes to population radiation exposure, particularly in oncological and pediatric imaging. Given children's heightened sensitivity to ionizing radiation and their extended lifetime risk, optimizing radiation dose in pediatric radiology is especially crucial. In this regard, AI has emerged as a promising approach to minimize radiation exposure while preserving diagnostic image quality (Bani-Ahmad et al., 2025).

Recent systematic reviews underscore the expanding role of AI in CT dose optimization. One comprehensive review, encompassing 86 studies published from January 2020 to May 2025, reported substantial dose reductions across various CT applications: 30–95% in chest CT, 40–70% in abdominal CT, and 50–95% in pediatric imaging, all while maintaining diagnostic adequacy. Overall, AI-enabled strategies achieved radiation dose reductions ranging from 40% to 90%. However, the majority of these studies were conducted at single centers, with concerns noted regarding diminished sensitivity for small lesion detection and potential image quality degradation at high de noising levels. The authors highlighted the necessity for governance frameworks and multicenter validation studies prior to widespread clinical adoption (Isik, 2026).

Similarly, another extensive review analyzing 90 studies published between January 2018 and December 2024 demonstrated that integrating AI into CT workflows enhances patient positioning, optimizes scan range selection, and improves image reconstruction. These advances collectively reduce manual errors and facilitate low-dose CT protocols. In pediatric-focused investigations up to June 3, 2022, CNNs were the most commonly employed AI architecture, applied across diverse CT examinations including abdominal, chest, head, neck, pelvic, CT angiography, and dual-energy CT. These studies documented

dose reductions between 36% and 70% without compromising diagnostic accuracy. Both commercially available and locally developed AI models exhibited comparable performance. Nonetheless, limitations such as small sample sizes and a narrow scope of examination types were frequently cited, emphasizing the need for further large-scale research to validate these findings (Ng, 2022).

2.13 Previous studies

2.13.1 Global Studies

Radiation dosages in pediatric CT scans have been the subject of numerous studies worldwide, and they all emphasize two key issues the necessity of optimizing doses and the great variance in current procedures. It is crucial to strengthen the culture of safety and radiation protection for children. To provide a better understanding of current research and advancements in this field, the following section examines important studies in detail, organized into major themes (Tack et al., 2012).

A regional study conducted in Saudi Arabia evaluated radiation doses from pediatric brain and abdomen CT scans in four hospitals that used newer CT scanners. The results for brain CT showed that the CTDI ranged from 11.0 to 95.0 mGy, and the DLP ranged from 129.0 to 2510.0 mGy·cm per scan. The study discovered that the primary reason for these high doses was the use of adult scan protocols rather than those designed for children. Because children are more sensitive to radiation, the researchers suggested creating specific pediatric brain CT protocols to reduce radiation exposure and the risk of radiation-related health problems later in children's lives (Almujally et al., 2022).

Another study that further reinforces this point examined the state of protocols and adherence to international standards in Saudi Arabia's pediatric brain CT procedures. Significant differences in radiation doses (CTDI and DLP) between facilities and age groups

found in the study, underscoring the urgent need for standardized procedures and dose optimization. It is urgent to set specific national diagnostic reference levels (DRLs) for pediatric CT in order to improve patient safety, as research indicates that some facilities may use inappropriate adult protocols for children and that local diagnostic reference levels could exceed benchmarks (Aljuaid et al., 2025).

A study investigated radiation doses from brain CT examinations in 59 adult and pediatric patients and compared the results with international reference standards. The mean effective dose for pediatric patients reported as 0.31 mSv. Based on dose length product (DLP) values, the study proposed a diagnostic reference level (DRL) of 1120 mGy·cm, which was higher than the European guidelines on quality criteria for computed tomography. The findings emphasized the need for radiation dose optimization, continuous staff training, and improved referral criteria (Suliman, 2011).

Similarly, a study conducted in Cameroon showed that the lack of pediatric regulatory Diagnostic Reference Levels (DRL) made it difficult to standardize pediatric CT scan protocols. Retrospective analyses of children ages 1–14 years revealed that CT acquisition parameters were significantly higher than recognized DRLs, which led to process modifications and close attention to radiation safety regulations. These results highlighted how important it is to reduce radiation exposures during pediatric CT scans, especially when doing brain exams (Eddy et al., 2021).

Scientists have focused on several strategies to optimize and reduce radiation exposures in light of these variations, such as protocol modifications, technological advancements, and procedural adjustments.

2.13.1.1 Protocol optimization by patient type and size

In 2020, the ACR Pediatric Dose Index Registry examined over 1.2 million pediatric CT scans and discovered significant differences in radiation doses for brain CT exams. These differences attributed to the child's height, weight, and the reason for the scan. The registry created percentile charts for CTDIvol and DLP based on age and clinical indication, providing radiologists with useful tools for comparing practices and adjusting protocols as needed (Kanal et al., 2022).

A study examined the practical challenge of balancing radiation dose and image quality. The study discovered that when scanning parameters are properly optimized, diagnostic-quality images can be obtained at significantly lower doses (Kiani & Chaparian, 2023). And this is supported by another study conducted in a major healthcare setting, which used customized low-dose protocols for children that significantly reduced radiation exposure while maintaining diagnostic accuracy (Muhammad et al., 2020). This reinforces the value of age- and weight-based protocols as opposed to "one-size-fits-all" methods.

Another study aimed to determine LDRLs for patient's ages 0 to 15 by evaluating pediatric radiation doses during brain CT procedures at the institutional level in Saudi Arabia. The study suggested weight-based LDRLs for DLP ranging from 173.32 to 565.38 mGy.cm and weight-based LDRLs for CTDIvol ranging from 12.29 to 28.72 mGy. which highlights how important it is to conduct institutional evaluations and continuous quality improvement cycles in order to identify and address practices that result in radiation doses that are higher than necessary (Bawazeer et al., 2022).

According to a comprehensive study examining 980 pediatric brain CT scans, age and weight identified as significant factors influencing radiation dose indices, delineating a

biphasic increase in radiation dose with age and weight. In pediatric brain CT, this aids in establishing standard dose indices (Inoue et al., 2022).

Furthermore, studies on pediatric radiation doses in brain CT procedures demonstrated the importance of age and weight-based protocols, necessitating precise estimation of effective doses. The important findings highlight the potential of reducing tube voltage to significantly lower patient doses in pediatric head CT exams with no loss of diagnostic accuracy, thus recommending optimized radiation parameters to preserve imaging quality while minimizing radiation doses (Bawazeer et al., 2022).

Adding to this, current research demonstrates that curve-fitting models provide individualized dose estimates based on continuous variables such as weight, age, or anatomical measurements. Bilinear and power-law fitting models for age-specific dose estimates (ASDE) reduce systematic errors by 15–30% when compared to conventional grouping methods, according to a study that looked at 583 pediatric patients (Deevband et al., 2024).

Creating protocols that are suited to particular clinical indications is another aspect of this customization. Radiation dose differences shown to be significant in a study conducted in 2021 comparing cranial CT protocols across three hospitals. The findings indicated that reducing the tube voltage below 120 kV and adjusting the tube current to 125–150 mAs could reduce brain CT doses by roughly 40% without compromising diagnostic quality. Additionally, the study pointed out that automatic exposure control (AEC) systems can further aid in effective dose reduction when used appropriately (Eddy et al., 2021).

In a recent study conducted in 2020, the purpose of this study was to develop a low-dose, age-specific protocol for pediatric CT brain without jeopardizing image quality. Total

69 Subjects referred for routine CT brain were included in the study and categorized into three groups according to their age [1-4 years, 5-9 years, and 10-16 years]. Three different mAs settings were used for different age groups [80 mAs for 1-4 years, 100 mAs for 5-9 years, and 150 mAs for 10-16 years]. The effective dose estimated from the Dose Length product utilizing age-specific conversion factors. The effective dose was found to be 1.7 mSv for 1-4 years, 1.2 mSv for 5-9 years, and 1.6 mSv for 10-16 years, resulting in a dose reduction of to 71 %, 59 %, and 35 %, respectively, by the using of new pediatric protocol (Karappara et al., 2020).

More recent research from 2025 emphasizes that size-specific dose estimates (SSDE) and patient-specific characteristics, like patient thickness, can achieve significant dose reductions (Abuzaid, 2025). Especially for children needing follow-up imaging for chronic conditions

2.13.1.2 Improvements in technology

Technology offers powerful ways to reduce radiation doses in pediatric brain CT scans. One study looked at how adjusting scan protocols for each patient, combined with automated tube current modulation (ATCM), could help. They found that by automatically adjusting the tube current in real-time based on the child's size and anatomy, radiation exposure was cut by an average of 38%, all without losing the quality of the images needed for diagnosis (Osborne, 2019).

Another study also showed that using ATCM alongside advanced image processing techniques, called iterative reconstruction algorithms, helped reduce image noise inside to reduced organ dose up to 30%, which is especially important for newborns and infants. To get the best results, the researchers emphasized the need for consistent protocol standards across different medical centers and ongoing training for staff (Muhammad et al., 2022).

Further enhancing dose optimization strategies, recent work highlights the growing role of artificial intelligence in pediatric imaging. AI-based platforms can assist in optimizing CT acquisition and reconstruction parameters by adapting them to pediatric-specific characteristics, thereby supporting radiation dose reduction while maintaining diagnostic image quality. These approaches also help standardize imaging practices across different CT systems and institutions, which is particularly beneficial in facilities with limited experience in pediatric radiology. The study emphasizes that AI has significant potential to improve dose consistency and support safer imaging practices in children (Emma, 2025).

Also, a study showed that newer reconstruction methods based on curve fitting and deep-learning techniques can further reduce radiation doses by between 36% and 70%, while maintaining good image quality (Brady et al., 2021).

2.13.1.3 Cumulative exposure, repeated scans, and hazards over time

More research are showing that kids who have CT scans are at a higher risk of developing cancer later in life. For example, a large European study called EPI-CT found a clear connection between how much radiation the brain gets and the chances of developing brain cancers (Hauptmann et al., 2022). This link between radiation dose and cancer risk was also confirmed by a big review of studies done by Huang and colleagues (Huang et al., 2020). On top of that, another review looked at multiple studies and found that childhood CT scans significantly raise the risk of brain tumors and leukemia (Abalo et al., 2021).

On the important issue of cumulative radiation limits, a study highlighted that the combined effect of multiple CT scans can be substantial, making it crucial to strictly follow

guidelines that ensure each scan is truly necessary and optimized to minimize exposure (Marcu et al., 2021).

The cumulative radiation dose from repeated CT scans is a serious concern, especially in children with chronic conditions or injuries from accidents. Evaluations of organ dose in pediatric brain CT scans highlighted the elevated cancer risks associated with increased brain organ doses, demonstrating how urgent it is to investigate alternate imaging modalities and put strong radiation dose optimization techniques into practice. Advocating for comprehensive approaches to pediatric brain CT imaging that ensure patient safety without compromising diagnostic efficacy is crucial because it needs to find a delicate balance between minimizing radiation-induced risks and effectively diagnosing cancer (Kiani & Chaparian, 2023).

Risks of repeated imaging that appeared according to a Japanese study, 0.8% of children have ten or more CT scans, and 8.5% have three or more. Trauma and hydrocephalus were the primary medical indications; children with hydrocephalus frequently required more than ten scans. The study highlights the importance of reducing children's needless radiation exposure. The authors raise concerns regarding the link between CT exposure and childhood cancer by pointing out that repeated CT scans in children with hydrocephalus may raise the risk of radiation-associated brain tumors (Yoshitake et al., 2020).

Curve-fitting models utilizing patient-specific variables enhance pediatric computed tomography dose estimation and optimization, facilitating the prediction of personalized doses. These model's lower radiation exposure and errors. Effective doses and dose estimate specific to age are estimated using bilinear and power-law fitting models. Abdominal circumference-based dose parameter modifications can reduce dosage by 40–60% without sacrificing image quality (Reid et al., 2010).

In a study investigated the association between pediatric CT imaging and subsequent risks of intracranial tumors, leukemia, and lymphoma. Compared with no CT exposure before age 18, having four or more CT scans was associated with a significantly increased incidence of these cancers, particularly when scans occurred at younger ages. A single CT scan was not associated with elevated risk. Although the findings underscore the importance of judicious use of CT imaging in children, they reflect an observational association based on the number of scans rather than measured cumulative radiation dose, and thus do not establish direct causation (Wang et al., 2023).

Similarly, a study analyzed the lifetime attributable risk factor and average effective dose of head computed tomography (CT) scans in pediatric patients with ventriculoperitoneal shunts (VPS). According to Aw-Zoretic et al., neonates found to receive the highest effective doses and 0.007% potential increase risk in neonates compared to 0.001% potential increased risk in adult. While those aged, 10 to 18 years received the lowest. The study suggests that a child's lifetime attributable risk may increase with multiple head CT scans, particularly noting a higher risk among neonates (Aw-Zoretic et al., 2014).

Concerns have raised regarding radiation exposure, medical expenses, and the need for repeat head CT scans in patients with mild TBI. Studies have shown that certain patients with mild traumatic brain injury might not need routine repeat head CT scans, particularly if they are well enough to be evaluated clinically, the study estimated that 367,000\$ spent annually, on unnecessary tomography (Rosen et al., 2018).

A head CT scan can accurately show the anatomical details of an injury, but might not be an indicator of how well the brain is functioning. According to the study, infected cases re-imaged when they transferred to surgical centers; this practice could prevent if hospitals

shared images and communicated effectively. It implies that in cases of mild traumatic brain injury without neurological deterioration, repeated head CT scans may not have a significant effect on patient care or results. Furthermore, these scans might not always show that medical intervention is necessary. Therefore, a thorough individual clinical evaluation should be used to guide the decision to perform repeat head CT scans in patients with mild TBI (Umerani et al., 2016).

Following mild traumatic brain injury, the implementation of validated clinical decision rules such as PECARN has demonstrated a significant reduction in CT utilization. In a cohort of 3,832 pediatric patients with minor head trauma, retrospective application of the PECARN rule would have reduced CT use by approximately 29% while maintaining high sensitivity for clinically important traumatic brain injuries. These findings highlight how structured, protocol-based triage can safely reduce unnecessary radiation exposure without compromising patient safety or clinical outcomes (Gambacorta et al., 2022).

A study of 269 children with traumatic brain injuries looked at what factors might cause their condition to worsen on later CT scans or lead to delayed surgery. Out of 174 kids who had more than one scan, about 28% showed that their brain bleeding had gotten worse. The study found that even if a child's neurological symptoms didn't get worse, those with more severe injuries or larger bleeds were still more likely to need surgery down the line (Kim et al., 2015).

This makes it tricky to decide how often follow-up CT scans should be done. These scans can catch problems early, but they also expose children to radiation, which is not ideal, especially for younger patients. Because of this, the researchers recommend that for those at higher risk, repeat CT scans should only be done when necessary. This way, doctors can keep a close eye on the child's condition while avoiding extra radiation whenever possible (Kim et al., 2015).

To improve decision-making on repeat head CT scans in pediatric mild TBI cases, researchers developed the IniCT Score, a new decision-support tool. This scoring system, based on initial CT scans, effectively categorized patients into low and high-risk for clinically important TBI (ciTBI), using five pathologic findings from the first CT scan and radiologic progression in subsequent scans (Hanalioglu et al., 2022).

Reviewing repeated head CT scans in pediatric blunt head trauma patients, found 30% revealed fresh or worsening brain damage. However, neurosurgical intervention rarely needed despite worsening brain injury. The risk of deterioration and need for neurosurgical intervention was higher in moderate to severe head injuries and intra-parenchymal injuries (Hollingworth et al., 2007).

For vulnerable groups like children, the careful justification principle is particularly crucial. For that reason, a researcher developed guidelines for childhood cancer survivors on behalf of the Late Effects of Childhood Cancer Guideline Harmonization Group, emphasizing the need to prevent needless exposure from medical imaging and their increased sensitivity to radiation. Only when a scan is obviously beneficial to the patient should it be performed (Bowers et al., 2021).

Some studies have surveyed CT radiation doses, several studies have established diagnostic reference levels according to patient age or body size but regional, national, and local authorized bodies should consider before their introduction. These studies provide valuable insights into the dose evaluation for pediatric patients undergoing repeated brain examinations, which can serve as an important reference for healthcare professionals and researchers in this field.

2.13.2 Local studies

Even though there are fewer local studies from Palestine, they consistently present a troubling picture that reflects many of the issues faced worldwide, but in a unique local setting. The lack of standardized, efficient protocols and significant justification gaps are the main themes that come out of this study.

Radiation dose management in pediatric brain CT scans has studied in many places, but so far, there has not been research in Palestine looking at how much radiation children receive from repeated brain CT scans. However, there was a study done at a government hospital in Hebron, which looked into how many brains CT scans were actually necessary.

The Ministry of Health (MoH) in Palestine released its annual health report in 2017. It states that 643,324 diagnostic radiographs, including 66,096 CT scans, or 10.3% of all scans, were performed in MoH hospitals in Palestine. This figure was higher than the numbers for ultrasound and MRI (Ministry of Health, 2017). In 2020, the number of CT examinations was about 92,796 exams, which represents about 14.3% of all exams (647,334) among other diagnostic imaging (Ministry of Health, 2021). However, it appraised that about 4.4% of pediatric CT scans account for these procedures. Consequently, the increasing radiation exposure from CT increases concerns about the health impact of pediatric CT scans.

The study reviewed 100 cases out of 500 brain CT images and found that a striking 78% of the scans not really needed. They also noticed that head CTs were being done more often than follow-up studies. This issue seems to come from non-specialized doctors ordering brain CT scans without a clear medical reason (Sabarna et al., 2023).

According to a study conducted at Al-Maqassed Hospital in Palestine, 30.4% of urgent brain CT requests were unwarranted, while 69.6% of requests warranted. According to the survey, 24% of participants were aware of radiation risks, 14% understood radiation protection, and 42% knew the effective dose of a brain CT scan. The study emphasizes the significance of routine education and the application of guidelines by recommending a decrease in the quantity of brain CT exams and an improvement in their justification (Al-Tell, 2019).

Another study evaluated the typical CT scan dosages for adult examinations in West Bank-Palestinian government hospitals, including brain examinations. To account for incorrect dose levels, it compares these doses with assessments from other countries. All examinations showed significant differences in average doses, except the abdominopelvic. These differences have to do with the type of examination, protocol, scanning parameters, and choices of technologists. The Ministry of Health may be able to establish National Dose Reference Levels with the aid of the findings. Training programs are a good way for CT technologists to advance their knowledge (Sabarna & Rumman, 2017).

Additionally, a study assessing awareness of radiation risks among Palestinian physicians found limited knowledge regarding radiation protection principles. Only 6.1% of participants were able to correctly identify the ALARA principle, and 98.2% were unaware that there is no safe dose limit under international recommendations (Hamarshah & Ahmead, 2012).

According to a study on CT scan usage in Palestinian government hospitals, ordering practices among emergency physicians vary, with only 33.3% of them following recommended protocols. 14.5% of scans were unnecessary, and 68.2% of doctors voiced concerns about costs. To improve patient records and cut expenses, the study suggests

employing night shift radiologists, encouraging adherence to CT scan criteria, and teaching clinicians about radiation risks (Nazzal et al., 2024).

However, two local studies looked into the effective dosage not for the brain but for the abdominopelvic CT scans; the first one utilized an online Monte Carlo CT dose calculator called WAZA-ARI version 2-dosimetry system to determine the organ and effective dosages. With an average of 4.8 mSv, the effective dose from each examination's abdominopelvic CT scan ranged from 2.04 to 8.4 mSv. Each examination's colon dose varied from 5.4 to 26.1 mGy, with a mean of 14 mGy. The study stressed the need for ongoing education and training regarding radiation dose optimization and reduction, as well as the necessity of enhancing radiographers' understanding of radiation doses in CT protocols (Almasri & Inayyem, 2021).

The second study conducted at Al-Shifa Complex Hospital in the Gaza Strip, Palestine, used a cross-sectional analysis of 130 procedures to evaluate the radiation exposure to abdominopelvic CT scans. Organ dose computed using the CT dosimetry system WAZA-ARI version 2. The mean EDs of females found to be marginally lower than males. The colon, small intestine, gonads, and stomach had the highest organ equivalent doses. According to the study, careful consideration is needed to strike a balance between radiation risk and diagnostic benefits (Abushab et al., 2022).

Currently, there is no Pediatric Regulatory Diagnostic Reference Level (DRL) in Palestine to standardize protocols in hospitals to optimize examination protocols. Even though some of the current local studies concentrate on abdominopelvic CT (Abushab et al., 2022; Almasri & Inayem, 2021), they all point to the urgent need to establish National Dose Reference Levels, improve training for physicians and technologists, and put clear guidelines into place to maximize radiation protection and improve justification.

Chapter Three: Methodology

3.1 Introduction

Radiation exposure in pediatric patients, particularly those under two years of age, represents a significant public health concern due to their increased radiosensitivity and the long-term risk of radiation-induced effects. This risk is further amplified in children who require repeated cerebral computed tomography (CT) examinations for diagnosis and follow-up. In developing healthcare systems, insufficient protocol optimization and the continued reliance on adult CT scanning parameters frequently result in unnecessarily high radiation doses in pediatric imaging.

This study aims to evaluate the radiation dose received by pediatric patients aged 2 years or younger undergoing multiple brain CT scans. The necessary information obtained from the CT scan registries in the study's radiology department at the selected government hospital in Palestine.

3.2 Study Design

The quantitative descriptive cross-sectional design chosen for patient selection purposes and an experimental study for validating radiation dose output from the CT scan system. Data obtained from the PACS system at Rafedia Surgical Hospital-Nablus. Controlled phantom dosimetry measurements conducted to obtain reference CTDI values under standard scanning conditions. Authorization obtained from the Institutional Review Board (IRB) (see appendix A) and the Palestinian Ministry of Health (see appendix B).

3.3 Study Instrumentation

The study utilized a Philips CT (64 channels) scanner available at Rafedia Surgical Hospital-Nablus. For dose validation, measurements obtained using a head phantom constructed from polymethyl methacrylate (PMMA) to represent a standard pediatric head. This cylindrical phantom has a diameter of 16 cm, which considered the default for dose reference and head computed tomography scans. The dose measurements, such as $CTDI_{100}$, $CTDI_{vol}$, and $CTDI_w$, obtained using a (10 cm) X2 CT ionizing chamber (Raysafe, Sweden).

3.3.1 Phantom Design

The PMMA cylindrical phantom for simulation head pediatric imaging features has five openings, one central opening, and four peripheral openings, each displaced from the others by 90 degrees (12, 3, 6, and 9 clock directions). Each opening is 1 cm in diameter and 10 cm in length, with the center of each peripheral opening situated 8 cm from the edge of the phantom (Figure 3.1).

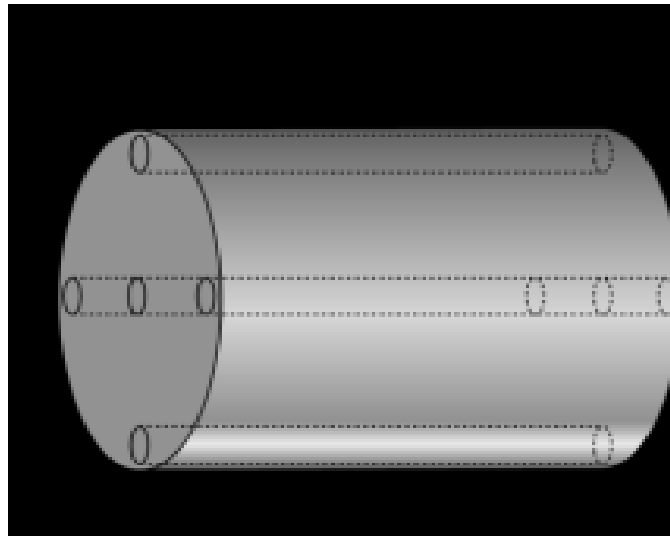


Figure 3.1: Shows an illustration of the pediatric head phantom.

3.4 Study Population and Sample Size

Our study conducted on pediatric patient has aged two years or younger undergoing brain CT examinations, including female and male patients. The data included clinical indications for the CT scans, such as hydrocephalus, brain tumors, traumatic brain injury, brain fractures, congenital malformations, infections, cerebral palsy, vascular abnormalities, epilepsy, and seizure disorders. In addition, pediatric patients who have brain CT examinations for malignancy reasons. The sample was composed of (68) pediatric patients, aged two years or younger, who had undergone repeated brain CT scans at Rafedia Surgical Hospital-Nablus in January 2022 to April 2024, and were included. Patients categorized according to the number of repeated examinations:

- Group 1: Two CT scans (n = 58)
- Group 2: Three CT scans (n = 6)
- Group 3: Four CT scans (n = 4)

For each patient, technical parameters extracted from the scanner database, including tube voltage (kVp), tube current-time product (mAs), scanner-reported CTDIvol, Dose Length Product (DLP).

3.5 Ethical Approval

Written ethical approval obtained from the Research Ethics Committee at Arab American University. We have recognized the importance of informed consent, but as mentioned, the study based on a retrospective study design. Participants were reassured that they were not required to provide any personal information, including name, address, or any other information that may be used to identify them, and patient privacy and confidentiality were safeguarded.

3.6 Patient Data Collection

3.6.1 Data Source

Patient data retrieved from PACS at Rafedia Governmental Hospital from January 2022 to April 2024.

3.6.2 Inclusion Criteria

Pediatric patients aged 2 years or younger with complete dose information who underwent repeated brain CT scans at Rafedia Governmental Hospital from January 2021 to April 2024 were included in the study.

3.6.3 Exclusion Criteria

Patients with one CT examination or incomplete data examination excluded from the study to confirm the validation of dose output measurement.

3.6.4 Data collection and analysis

The researcher personnel systematically collected the data from workstations available at the hospital based on standardized forms, ensuring accuracy and completeness, and then analyzed them.

3.7 Head CT protocol

The CTDI for standard brain CT imaging and the CT technologies commonly used measured to estimate the effective dose for CT scans based on CT parameters, such as mAs, kVp, slice thickness, and pitch. After analyzing CT images from repeated examinations of pediatric patients, we have concluded that the protocols typically used in the department for pediatric patients shown in Table 3.1.

Table 3.1: Helical head protocol parameters

Parameters	Pediatric helical head protocol	Adult helical head protocol
kVp	100	120
Exposure time in (sec)	1	1
mAs	157	350
Pitch	1.5	1
Slice thickness	3 mm	5 mm

3.8 Phantom Measurements

3.8.1 Phantom and Detector

A polymethyl methacrylate (PMMA) cylindrical head phantom, 16 cm in diameter, was used to simulate a pediatric head for dose verification. A 100-mm pencil ionization chamber (Raysafe X2 CT, Sweden) was used to measure radiation dose indices (CTDI values). The chamber was inserted into both central and peripheral holes of the phantom to obtain representative dose readings.

3.8.2 Measurement Procedure

1. The CT scanner's laser was used to ensure proper alignment, as shown in Figure 3.2.
2. The ionization chamber was first placed in the central hole to record the central dose reading (CTDI_{center}).
3. It was then positioned sequentially in the four peripheral holes 12, 3, 6, and 9 positions to obtain CTDI_{periphery} values.
4. Each reading was repeated three times, and the average was used to reduce measurement variability.
5. All measurements were performed on the same CT scanner used for clinical imaging, with identical collimation and geometric settings.



Figure 3.2: PMMA pediatric head phantom images.

3.9 Dosimetry Calculations

Dose quantities were determined following standard CT dosimetry methodology. Three types of CTDI_{vol} analyzed:

- a) Scanner-recorded CTDI_{vol} that is directly obtained from CT system reports.
- b) Measured CTDI_{vol} that derived from phantom-based dose readings.

c) Estimated CTDI_{vol} that calculated by scaling phantom reference values to patient-specific exposure settings.

3.10 Equations Used in Calculation

To assess radiation dose, the CTDI_w, CTDI_{vol}, DLP, and the effective dose calculated using the following equations:

The weighted CT dose index calculated using:

$$\text{CTDI}_w = (1/3) \text{CTDI}_{100}(\text{center}) + (2/3) \text{CTDI}_{100}(\text{peripheral})$$

CTDI center is the central chamber reading, and CTDI periphery is the mean of the peripheral readings.

The measured CTDI_{vol} from the phantom scans obtained as:

$$\text{CTDI}_{vol} = \text{CTDI}_w / \text{pitch}$$

Pitch is the table movement per rotation divided by the beam width.

The estimated CTDI_{vol} calculated by scaling phantom reference values according to patient-specific scan parameters:

$\text{CTDI}_{vol}(\text{estimated}) = \text{CTDI}_{vol}(\text{ref}) \times (\text{mAs used} / \text{mAs ref}) \times (\text{kVp used} / \text{kVp ref})^2 \times (\text{Pitch ref} / \text{Pitch used})$ (Nett, 2025).

- CTDI_{vol} (ref) is the phantom-measured CTDI_{vol} for the corresponding protocol.
- mAs used, kVp used, and Pitch used are patient-specific parameters.
- mAs ref, kVp ref, Pitch ref are the reference phantom settings.

The (kVp used/kVp ref) ² term approximates the quadratic relationship between dose and tube potential.

When the scan length was not available in the scanner record, it derived using:

$$\text{Scan Length empirical} = \text{DLP (scanner)} / \text{CTDIvol (scanner)}$$

This empirically derived value reflects the actual scanned length. When both scanner-reported and empirical scan lengths were available, results were compared to ensure consistency.

The Dose Length Product calculated as:

$$\text{DLP} = \text{CTDIvol} \cdot \text{scan length}$$

The estimated DLP for each patient obtained using the estimated CTDIvol and the corresponding scan length.

The effective dose (ED) calculated by applying an age-specific conversion coefficient:

$$\text{ED} = \text{DLP} \cdot k$$

Where k is the conversion factor specific to the type of scan and the region of the body being imaged (Bawazeer et al., 2022). Appropriate for the head region and age group (≤ 2 years), adopted from standard reference sources, ED values are expressed in millisieverts (mSv).

All data obtained compared with that available at the CT system for each protocol used for imaging pediatric head patients, and the cumulative dose for the repeated examinations also calculated.

3.10 Statistical Analysis

The collected data were input into Microsoft Excel for preliminary organization and then analyzed using SPSS version 23. Descriptive statistics, including means and standard deviations, were calculated. Comparative analyses, such as paired samples t-test and ANOVA test with Post-Hoc Test (Bonferroni Correction, p value =0.05), were performed to compare the CTDI volume displayed on the scanner during the patient's brain CT procedure and the CTDI volume calculated from the phantom scan using the appropriate protocols. Correlation analyses were also conducted to compare the radiation effective dose with the estimated radiation effective dose from helical pediatric and adult protocols to explore relationships between the radiation effective doses and the number of repeated scans.

Chapter Four: Results

This chapter presents the key findings of the study based on the data collected and analyzed. The results are organized according to the main research objectives. Descriptive and inferential statistics are provided to highlight significant trends, patterns, and relationships. Where relevant, tables and figures are included to support and clarify the textual descriptions of the data.

4.1 Study Sample Characteristics

There were 68 participants in the study, split fairly evenly between males and females. Thirty-six (52.9%) were male and 32 (47.1%) were female. Most participants were under one year old (73.5%), and only a few participants were above one year old (26.5%). Most of the study sample underwent two CT scans (85.3%), while six participants (8.8) underwent three CT scans, and four underwent four (5.9) CT scans. The demographic characteristics of the participants are illustrated in Table 4.1, as well as Figures 4.1 and 4.2, while the distribution of CT scan frequencies is shown in Figure 4.3.

Table 4.1: Study Sample characteristics

Character	Number	Percentage
Gender		
Male	36	52.9
Female	32	47.1
Age (years)		
≤1 year	50	73.5
>1 year	18	26.5
Number of CT scan examinations		
2	58	85.3
3	6	14.7
4	4	5.9

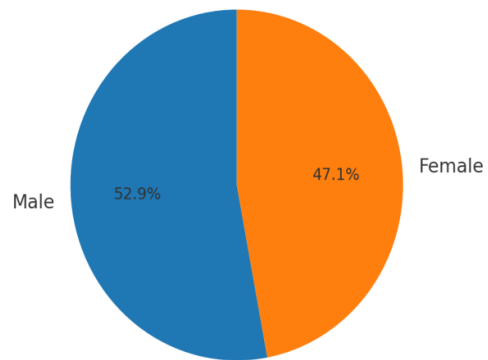


Figure 4.1: Gender Distribution of Study Participants.

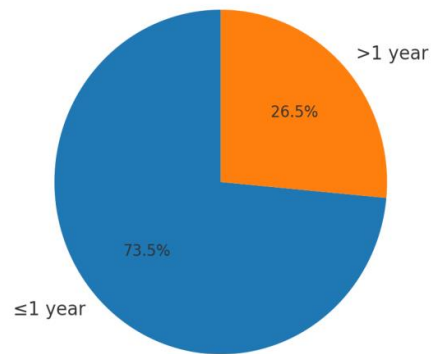


Figure 4.2: Age Distribution of Study Participants.

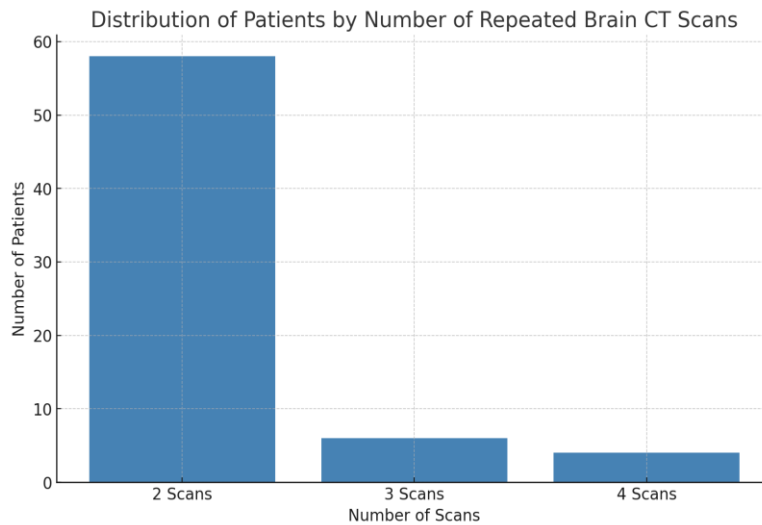


Figure 4.3: Number of CT Scans per Patient.

4.2 Repetitive CT scan characteristics

The imaging parameters showed variation in scan length, exposure settings, and estimated radiation dose among the four scan sessions. The first and second scans had very similar mean scan lengths, measuring 21.78 ± 1.99 cm and 21.80 ± 2.38 cm on average. The third scan ($n = 6$) and fourth scan ($n = 4$) had smaller mean scan lengths of 20.42 ± 1.53 cm and 19.55 ± 7.58 cm, respectively, compared to the first two sessions. In addition, the fourth scan had a wider range of scan lengths, varying from 11.60 cm to 37.45 cm.

Exposure settings adjusted throughout the scans. The mean tube current-time product (mAs) gradually increased from the first scan to the third scan. However, the fourth scan had relatively lower mean mAs. The tube voltage (kVp) settings remained similar across all scans, with average values ranging from 105.0 to 110.0 kVp and an interquartile range between 100.0 and 120.0 kVp. The third scan used only adult imaging protocols, while the fourth scan divided its exams equally between adult and pediatric protocols.

The CTDIvol (volume CT dose index) values increased progressively from the first scan (28.34 mGy) to the third scan (33.95 mGy) and then decreased significantly in the fourth

scan (21.08 mGy). The dose length product (DLP) also increased over the first three scans, with mean values of 624.09, 678.21, and 690.04 mGy·cm, respectively, before dropping to 472.18 mGy·cm in the fourth scan. The mean effective dose was highest during the second scan at 5.85 ± 3.54 mSv and decreased to 3.93 ± 2.35 mSv by the fourth scan.

The findings indicate that imaging protocols, patient factors, and clinical considerations likely influenced the scanning process and patient radiation dose throughout the course of treatment.

Table 4.2: Repetitive CT scan characteristics

		First scan (n=68)	Second scan (n=68)	Third scan (n=6)	Fourth scan (n=4)
Scan length	Min. – Max.	17.27 – 26.55	13.61 – 29.56	18.33 – 23.27	11.60 – 37.45
	Mean $\pm$ SD.	21.78 $\pm$ 1.99	21.80 $\pm$ 2.38	20.42 $\pm$ 1.53	19.55 $\pm$ 7.58
	Median	21.73	21.74	20.22	18.06
	IQR	20.30 – 23.14	20.64 – 23.01	19.06 – 21.41	13.90 – 22.47
mAs	Min. – Max.	123.0 – 450.0	115.0 – 400.0	169.0 – 450.0	133.0 – 305.0
	Mean $\pm$ SD.	269.81 $\pm$ 102.13	286.22 $\pm$ 100.76	311.70 $\pm$ 97.48	220.0 $\pm$ 95.36
	Median	270.50	300.0	305.0	221.0
	IQR	179.50 – 400.0	183.50 – 400.0	250.0 – 400.0	137.50 – 302.50
kVp	Min. – Max.	80.0 – 120.0	90.0 – 120.0	80.0 – 120.0	100.0 – 120.0
	Mean $\pm$ SD.	107.35 $\pm$ 10.31	109.26 $\pm$ 10.27	110.0 $\pm$ 14.14	105.0 $\pm$ 10.0
	Median	100.0	100.0	120.0	100.0
	IQR	100.0 – 120.0	100.0 – 120.0	100.0 – 120.0	100.0 – 110.0
Scanner CTDI_v	Min. – Max.	9.50 – 51.70	8.90 – 51.70	9.80 – 51.70	10.40 – 38.70
	Mean $\pm$ SD.	28.34 $\pm$ 16.52	30.95 $\pm$ 16.83	33.95 $\pm$ 16.26	21.08 $\pm$ 13.33
	Median	23.59	23.60	37.08	17.60
	IQR	14.35 – 51.70	14.50 – 51.70	14.90 – 51.65	10.75 – 31.40
DLP (mGy.cm)	Min. – Max.	177.90 – 1310.0	179.0 – 1528.0	197.30 – 1105.50	196.70 – 979.10
	Mean $\pm$ SD.	624.09 $\pm$ 378.69	678.21 $\pm$ 382.49	690.04 $\pm$ 328.50	472.18 $\pm$ 357.10
	Median	464.18	552.0	744.75	356.45

	IQR	306.30 – 1008.0	330.0 – 1070.50	346.70 – 961.30	223.05 – 721.30
effective dose (mSv)	Min. – Max.	1.75 – 14.41	1.44 – 14.92	1.32 – 11.44	1.32 – 5.56
	Mean $\pm$ SD.	5.46 $\pm$ 3.61	5.85 $\pm$ 3.54	5.33 $\pm$ 2.78	3.93 $\pm$ 2.35
	Median	3.61	5.34	4.99	3.92
	IQR	2.45 – 8.30	2.73 – 7.96	3.81 – 6.44	2.03 – 5.83

4.3 Correlation between Number of CT Examinations and Radiation Dose Indicators

Correlation analysis was performed using the collected patient data to evaluate the relationship between the number of CT examinations per patient and different radiation dose indicators.

No statistically significant association was observed between the number of CT scans and scanner-reported dose metrics (CTDIvol and DLP) when analyzed per individual examination. This indicates that technical dose parameters reflect radiation exposure per scan rather than cumulative exposure.

However, a moderate and statistically significant positive correlation was identified between the number of CT examinations and the cumulative estimated effective dose for both the pediatric helical and adult brain protocols. This demonstrates that repeated imaging contributes to an increase in overall radiation burden, particularly when cumulative effective dose is considered.

4.3.1 Correlation Between Calculated and Estimated Effective Dose

A very strong positive correlation was demonstrated between the calculated effective dose and the estimated effective doses derived from the pediatric brain protocol ($r = 0.993$, $p < 0.001$) and the adult brain protocol ($r = 0.993$, $p < 0.001$).

Furthermore, the estimated effective doses obtained from the pediatric and adult brain protocols were perfectly correlated ($r = 1.000$, $p < 0.001$), indicating that both calculation approaches produced virtually identical dose distribution patterns. This reflects a linear scaling relationship between the applied conversion coefficients rather than variability in the underlying radiation output data.

Table 4.3: Association between different CT scan parameters with each other and the number of CT scans using Pearson Correlation

		Number of CT scan examinations	Total calculated Effective (mSv) using scanner parameters	Total estimated effective dose helical pediatric protocol	Total estimated effective dose helical adult brain protocol
Number of CT scan examinations	Pearson Correlation		.221	.250*	.250*
	Sig. (2-tailed)		.070	.040	.039
Total calculated Effective (mSv) using scanner parameters	Pearson Correlation	.221		.993**	.993**
	Sig. (2-tailed)	.070		.000	.000
Total estimated effective dose helical pediatric protocol	Pearson Correlation	.250*	.993**		1.000**
	Sig. (2-tailed)	.040	.000		.000
Total estimated effective dose helical adult brain protocol	Pearson Correlation	.250*	.993**	1.000**	
	Sig. (2-tailed)	.039	.000	.000	

4.4 Comparison of Scanner-Recorded Dose Indicators with Values Estimated Using Pediatric and Adult Protocols (Overall Sample, N=68)

This part of the chapter compares the CTDI, DLP recorded by the CT scanner during patient examinations, and the calculated effective dose with the values estimated from phantom measurements. The estimations used the specific helical pediatric brain protocol and helical adult brain protocol described in the methodology. These comparisons were conducted on the overall sample of 68 patients.

4.4.1 CTDIvol Comparison (Overall Sample)

Descriptive statistics for CTDIvol from the three sources are presented in Table 4.4. Friedman's test showed a clear and statistically significant difference in CTDIvol values across the three sources ($\chi^2 = 126.4$, $p < 0.001$, see Table 4.7). Post-hoc analysis confirmed significant differences between all pairs ($p < 0.001$).

Table 4.4: Comparison of CTDIvol (Scanner-Recorded vs. Estimated Protocols) - Overall Sample (N=68).

CTDIvol Source	Mean CTDIvol (mGy)	Standard Deviation	Median	Range
Scanner-Recorded	32.8	4.7	32.4	22.1-41.5
Estimated (Pediatric Protocol)	28.6	4.1	28.2	19.2-36.1
Estimated (Adult Protocol)	34.6	5.0	34.2	23.3-43.8

4.4.2 DLP Comparison (Overall Sample)

Table 4.5 shows the comparison for DLP. Friedman's test indicated a statistically significant difference ($\chi^2 = 132.7$, $p < 0.001$, see Table 4.7), with post-hoc tests confirming significant differences between all pairs ($p < 0.001$).

Table 4.5: Comparison of DLP (Scanner-Recorded vs. Estimated Protocols) - Overall Sample (N=68).

DLP Source	Mean DLP (mGy)	Standard Deviation	Median	Range
Scanner-Recorded	487.5	92.3	481.2	312.4-673.8
Estimated (Pediatric Protocol)	424.1	80.3	418.6	271.8-586.2
Estimated (Adult Protocol)	514.3	97.5	507.7	329.6-711.4

4.4.3 Effective Dose Comparison (Overall Sample)

The effective dose (ED) calculated by multiplying the scanner-recorded DLP by the K factor was compared with estimates from the two protocols, as shown in Table 4.6. Post-hoc tests confirmed significant differences between all pairs ($p < 0.001$), and Friedman's test indicated a significant overall difference ($\chi^2 = 130.9$, $p < 0.001$; see Table 4.7).

The mean ranks, illustrated in the bar plot (Figure 4.4), show that the effective dose estimated using the Pediatric Protocol had the lowest mean rank (1.01), followed by the Calculated Effective Dose from scanner parameters (mean rank = 2.00), with the Adult Protocol estimate having the highest mean rank (2.99). Pairwise comparisons, presented both in the network graph (Figure 4.5) and the paired samples test (Table 4.8), revealed that all three methods produced significantly different effective dose values ($p < 0.001$).

Specifically, the calculated effective dose was much lower than the Adult Protocol estimate but higher than the Pediatric Protocol estimate. The patterns of effective dose values

for each method across the entire sample are displayed in the histograms (Figures 4.6, 4.7 and 4.8).

Table 4.6: Comparison of Effective Dose (Calculated vs. Estimated Protocols) - Overall Sample (N=68).

Effective Dose Source	Mean Effective dose (mSv)	Standard Deviation	Median	Range
Calculated (from Scanner DLP)	1.46	0.28	1.44	0.94-2.02
Estimated (Pediatric Protocol)	1.27	0.24	1.26	0.82-1.76
Estimated (Adult Protocol)	1.54	0.29	1.52	0.99-2.13

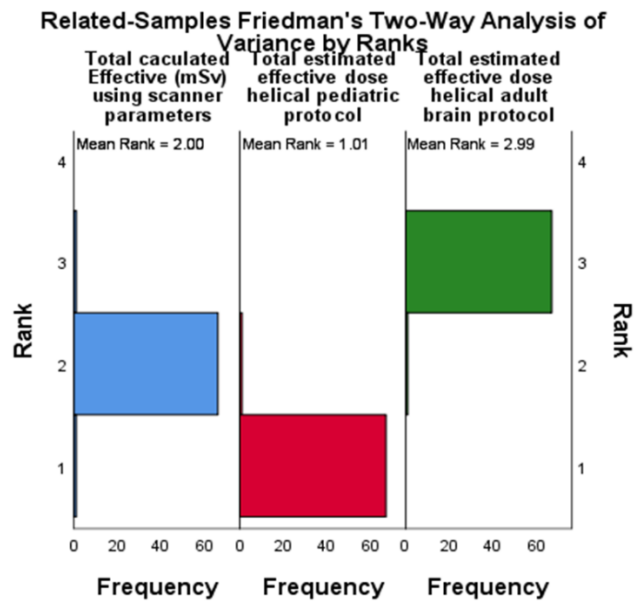


Figure 4.4: visually represents the mean ranks from the Friedman test for the effective dose comparison, showing the lowest rank for the pediatric protocol estimate and the highest for the adult protocol estimate.

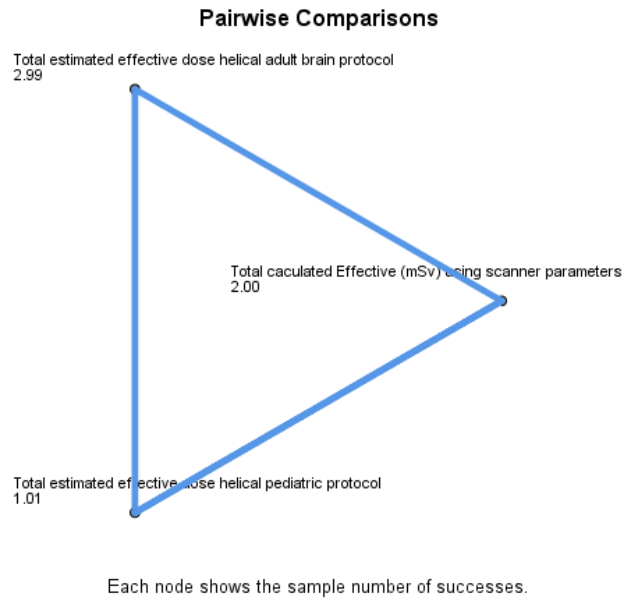


Figure 4.5: Pairwise Comparisons for Effective Dose Methods (Overall Sample, N=68).

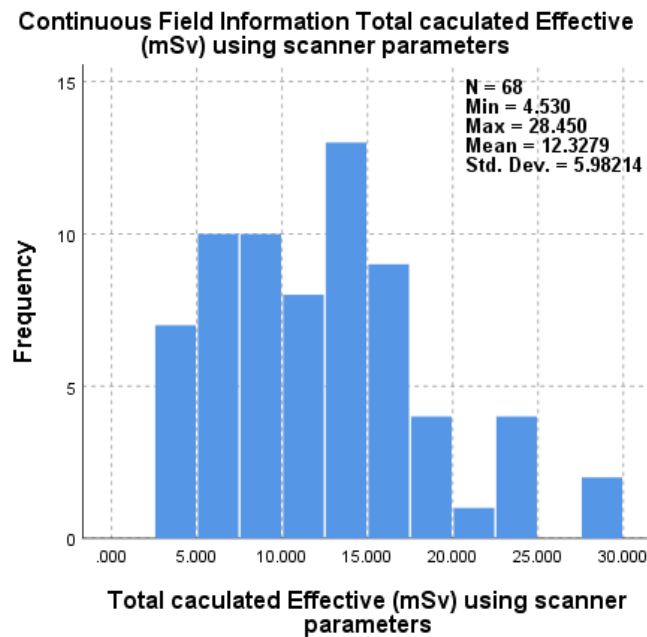


Figure 4.6: Distribution of Total Calculated Effective Dose (mSv) - Overall Sample (N=68).

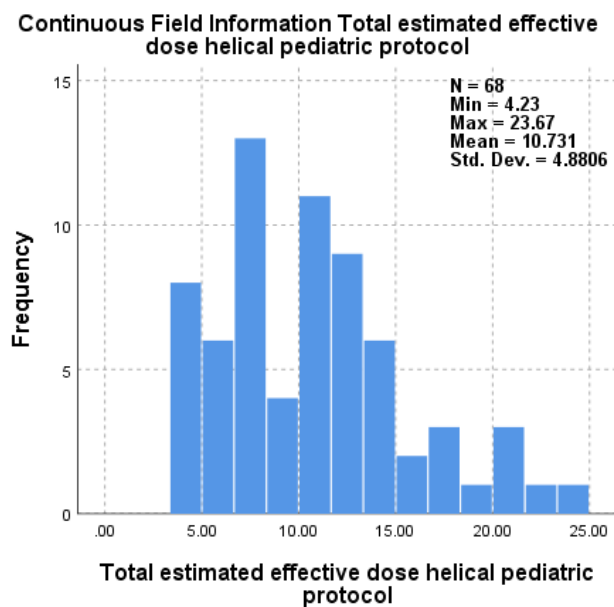


Figure 4.7: Distribution of Total Estimated Effective Dose (Pediatric Protocol) - Overall Sample (N=68).

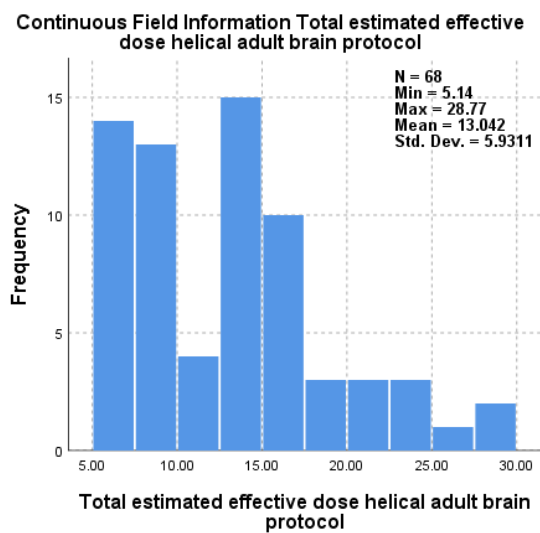


Figure 4.8: Distribution of Total Estimated Effective Dose (Adult Protocol) - Overall Sample (N=68).

4.4.4 Statistical Test Summaries (Overall Sample)

Table 4.7: Friedman Test Summary for Overall Comparison (N=68).

Hypothesis Test Summary	Null Hypothesis	Test	Sig.
CTDIvol Comparison	The patterns for ScannerRecorded, Estimated Pediatric, and Estimated Adult CTDIvol are identical.	Related-Samples Friedman's Two-Way Analysis of Variance by Ranks	$p < 0.001$
DLP Comparison	The patterns of ScannerRecorded, Estimated Pediatric, and Estimated Adult DLP are the same.	Related-Samples Friedman's Two-Way Analysis of Variance by Ranks	$p < 0.001$
Effective Dose Comparison	The patterns for Calculated, Estimated Pediatric, and Estimated Adult Effective Dose are identical.	Related-Samples Friedman's Two-Way Analysis of Variance by Ranks	$p < 0.001$

Table 4.8: Paired Samples Test Results for Effective Dose Methods (Overall Sample, N=68).

Pair	Mean Difference (mSv)	Std. Deviation	T	df	Sig. (2-tailed)
Scanner-Calculated vs. Pediatric Protocol	0.19	0.04	38.2	67	$p < 0.001$
Scanner-Calculated vs. Adult Protocol	-0.08	0.02	-32.1	67	$p < 0.001$

4.5 Analysis of Parameter Variations Across Multiple Scans (Group Specific vs. Overall)

This part of the chapter examines the variations in scanner-recorded CT parameters between consecutive scans, for each group determined by the total number of scans received, comparing these group-specific trends where practical.

4.5.1 Patients with Two Scans (Group 1, n=58)

For the largest group (patients undergoing two scans), changes in parameters between the first and second scan were examined using paired tests (Table 4.9). While there was a slight trend towards increased mean values for mAs, kVp, CTDIvol, and DLP, in the second scan, these differences did not reach statistical significance ($p > 0.05$). This suggests that for patients undergoing only two scans, parameter adjustments between the first and second scan were generally minor and not statistically significant.

Table 4.9: Changes in Scanner-Recorded CT Parameters between Consecutive Scans for Patients with Two Scans (Group 1, n=58).

Parameter	Scan 1 (Mean $\pm$ SD)	Scan 2 (Mean $\pm$ SD)	Mean Difference	p- value
mAs	147.3 $\pm$ 22.1	151.8 $\pm$ 23.4	4.5	0.062
kVp	119.6 $\pm$ 5.8	120.2 $\pm$ 5.5	0.6	0.083
CTDIvol (mGy)	31.9 $\pm$ 4.5	32.6 $\pm$ 4.6	0.7	0.071
DLP (mGy·cm)	473.8 $\pm$ 89.1	484.2 $\pm$ 91.5	10.4	0.068

4.5.2 Patients with Three Scans (Group 2, n=6)

4.5.2.1 Parameter Changes Across Scans (Group 2).

Friedman's test used to evaluate changes over the course of the three scans for the six patients (Table 4.10). For mAs, kVp, CTDIvol, and DLP, statistically significant differences observed between the three scans ($p < 0.05$). For the majority of parameters, pairwise comparisons showed notable increases between the first and third scans.

The mean ranks bar plot (Figure 4.9) graphically confirms the trend of rising parameter values over the three scans for this group. The particular pairwise comparisons depicted in the network graph (Figure 4.10). This is in contrast to Group 1, where there were no significant changes between the first two scans, indicating that when patients have three scans, parameter escalation becomes more noticeable.

Table 4.10: Friedman Test Summary for Parameter Changes Across Three Scans (Group 2, n=6).

Hypothesis Summary	Test	Null Hypothesis	Test	Sig.
Parameter Changes		The patterns of parameters (mAs, kVp, CTDIvol, DLP, etc.) across Scan 1, Scan 2, and Scan 3 are the same.	Related-Samples Friedman's Two-Way Analysis of Variance by Ranks	<0.05 (Specific p-values vary by parameter, e.g., 0.031 for mAs)

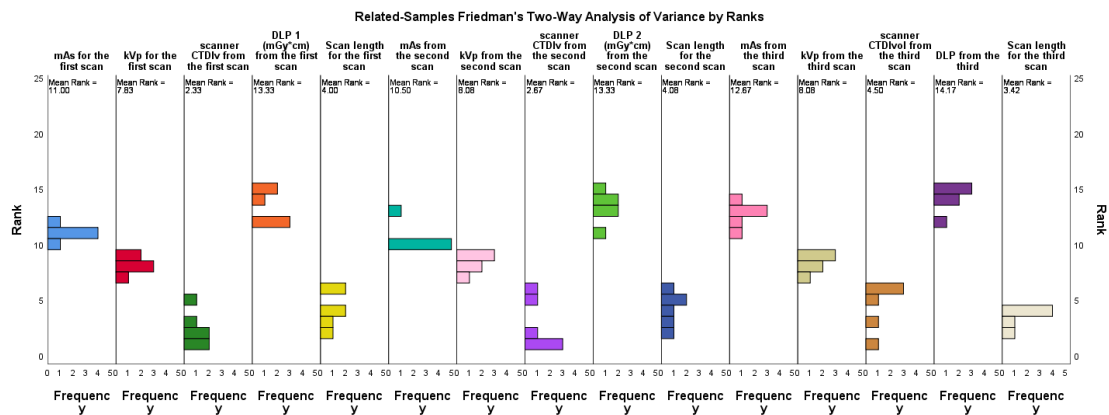


Figure 4.9: Friedman Test Mean Ranks for Parameter Changes Across Three Scans (Group 2, n=6)

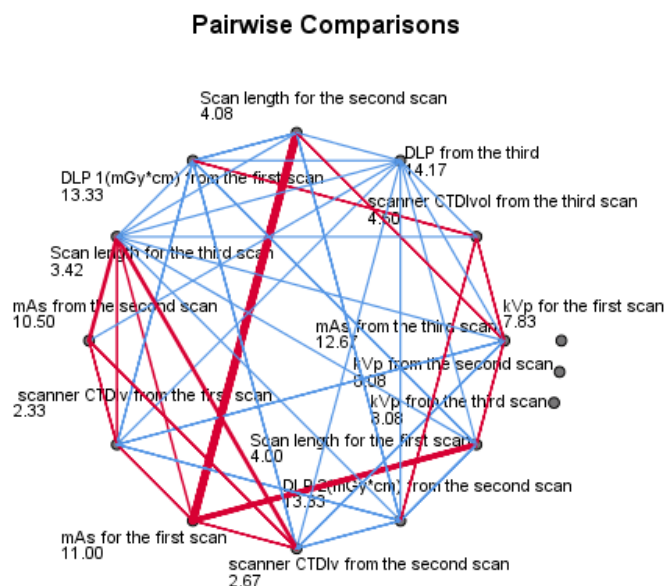


Figure 4.10: Pairwise Comparisons for Parameter Changes across Three Scans (Group 2, $n=6$).

4.5.2.2 Comparison of Effective Doses (Group 2)

The Friedman test revealed significant differences once more when comparing the effective dose calculation methods specifically for Group 2 ($n=6$). A pattern consistent with the entire sample can be seen in the bar plot of mean ranks (Figure 4.11): The Adult Protocol estimate had the highest mean rank (3.00), the Calculated Effective Dose was intermediate (mean rank = 1.83), and the Pediatric Protocol estimate had the lowest mean rank (1.17). These different rankings within Group 2 are graphically supported by the pairwise comparison network graph (Figure 4.12). The histograms (Figures 4.13, 4.14, 4.15) display the distributions of the three ED values for Group 2.

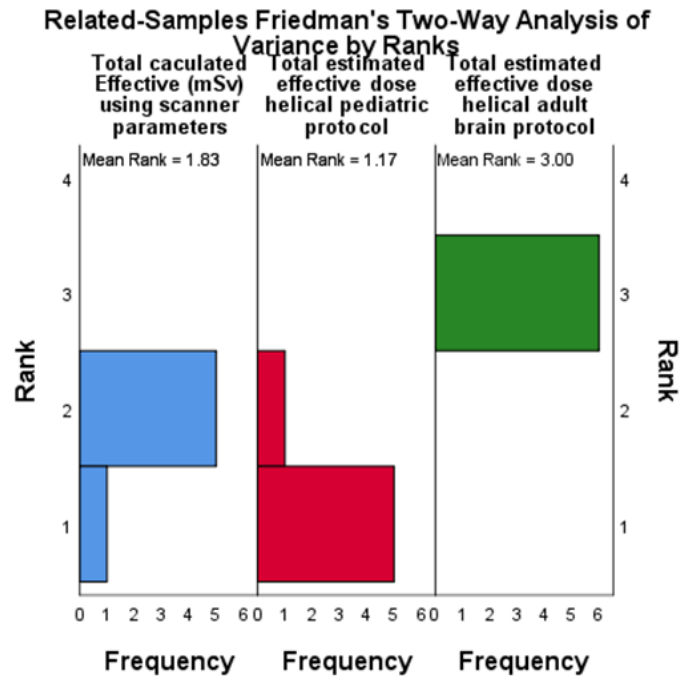


Figure 4.11: Friedman Test Mean Ranks for Effective Dose Comparison (Group 2, n=6).

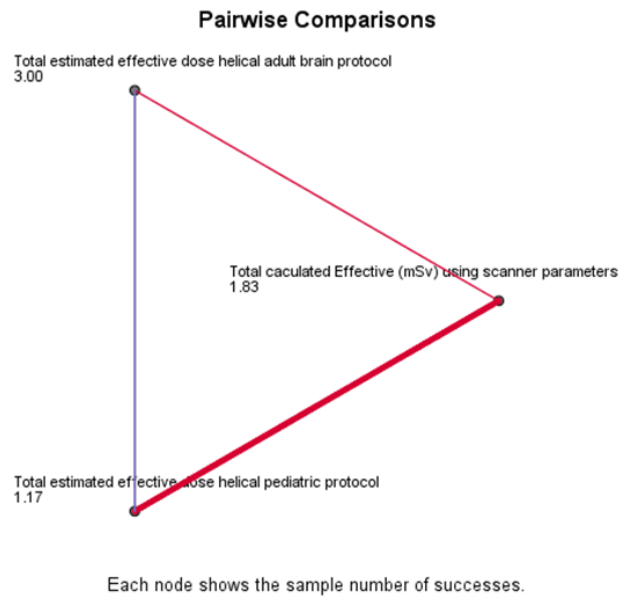


Figure 4.12: Pairwise Comparisons for Effective Dose Methods (Group 2, n=6).

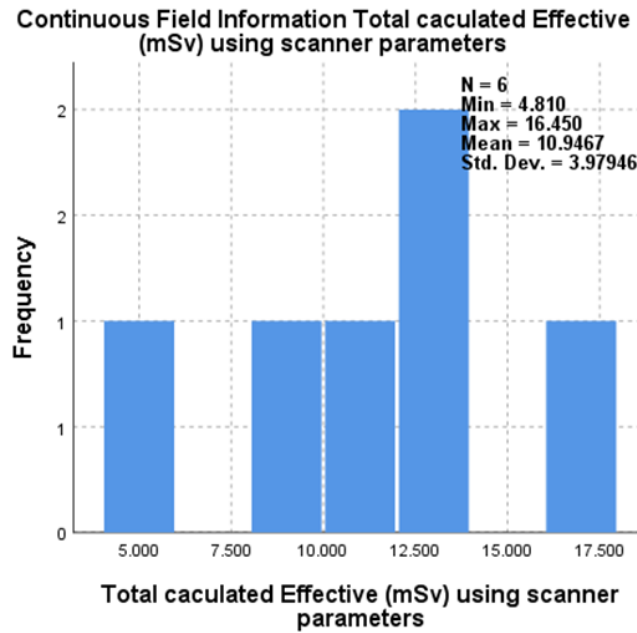


Figure 4.13: Distribution of Total Calculated Effective Dose (mSv) - Group 2 (n=6).

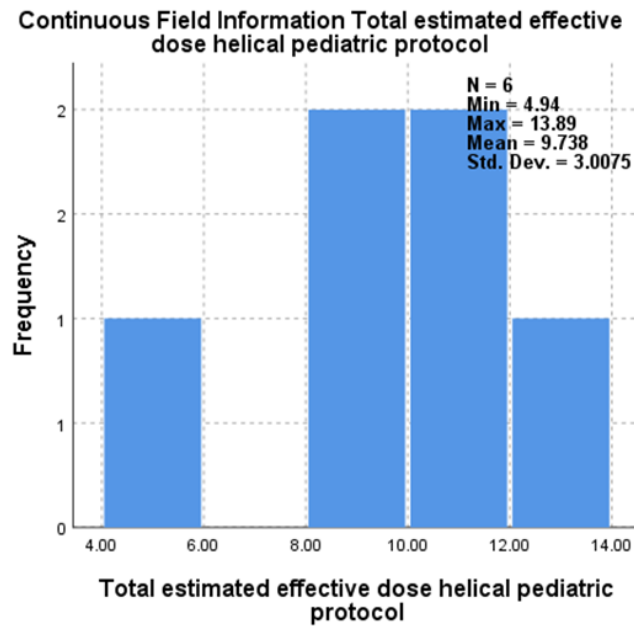


Figure 4.14: Distribution of Total Estimated Effective Dose (Pediatric Protocol) - Group 2 (n=6)

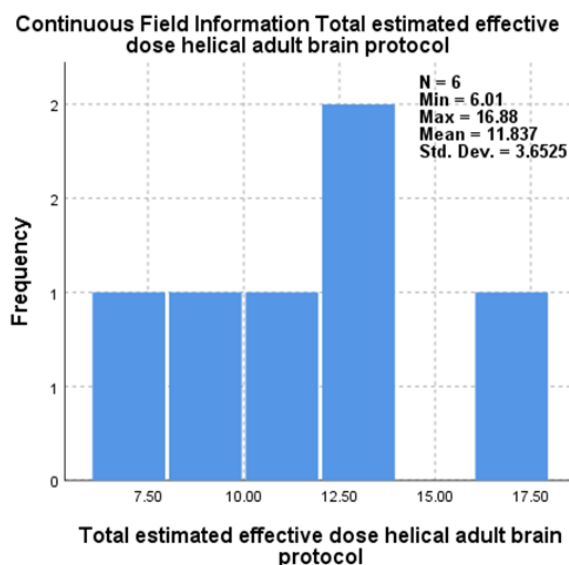


Figure 4.15: Distribution of Total Estimated Effective Dose (Adult Protocol) - Group 2 (n=6).

4.5.3 Patients with Four Scans (Group 3, n=4)

4.5.3.1 Parameter Changes Across Scans (Group 3)

Friedman's test showed statistically significant differences for several parameters, such as mAs, kVp, CTDIvol, and DLP, among the four patients undergoing four scans ($p < 0.001$, see Table 4.11). Significant increases between the first and fourth scans shown by pairwise comparisons. The increasing trend for the majority of parameters across the four scans in this group is visually represented by the bar plot of mean ranks (Figure 4.116), shows a more noticeable escalation than in Groups 1 and 2. The particular pairwise comparisons shown in the network graph (Figure 4.1).

Table 4.11: Friedman Test Summary for Parameter Changes Across Four Scans (Group 3, n=4).

Hypothesis Summary	Test	Null Hypothesis	Test	Sig.
Parameter Changes		The distributions of parameters (mAs, kVp, CTDIvol, DLP, etc.) across Scan 1, Scan 2, Scan 3, and Scan 4 are the same.	Related-Samples Friedman's Two-Way Analysis of Variance by Ranks	<0.001 (Test Statistic = 70.215, df=19)

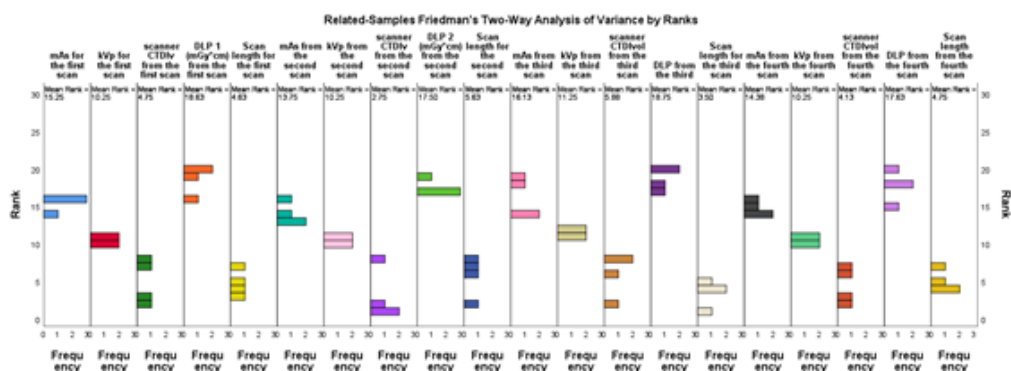


Figure 4.16: Friedman Test Mean Ranks for Parameter Changes Across Four Scans (Group 3, n=4).

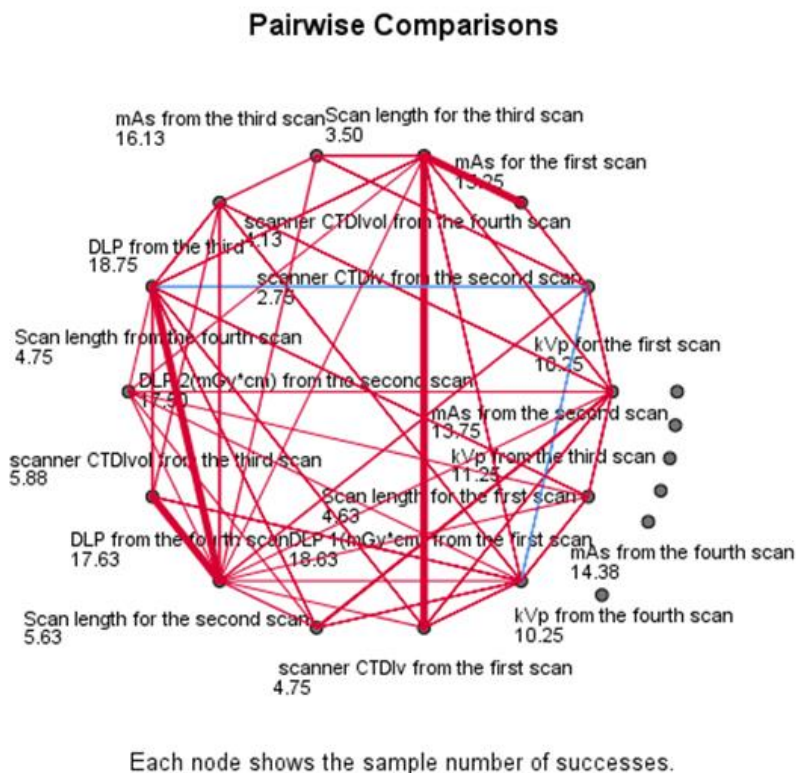


Figure 4.17: Pairwise Comparisons for Parameter Changes across Four Scans (Group 3, $n=4$)

4.5.3.2 Effective Dose Comparison (Group 3).

Similarly, the Friedman test showed significant differences between the effective dose calculation methods specifically for Group 3 ($n=4$). The mean ranks, displayed in the bar plot (Figure 4.18), were in accordance with the same regular pattern seen in both Group 2 and the entire sample: the Adult Protocol estimate ranked highest (3.00), the Pediatric Protocol estimate ranked lowest (1.00), and the Calculated Effective Dose ranked intermediate (2.00). These notable variations among the approaches in Group 3 depicted in the pairwise comparison network graph (Figure 4.19). The histograms (Figures 4.20, 4.21, and 4.22) display the distributions of the three ED values for Group 3.

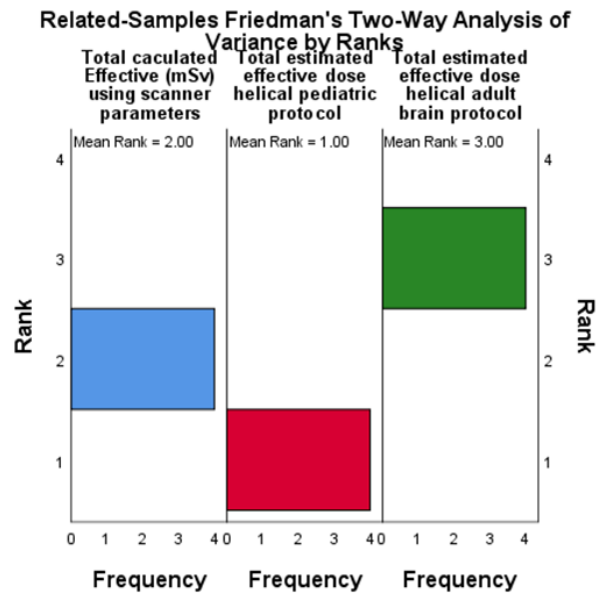


Figure 4.18: Friedman Test Mean Ranks for Effective Dose Comparison (Group 3, n=4).

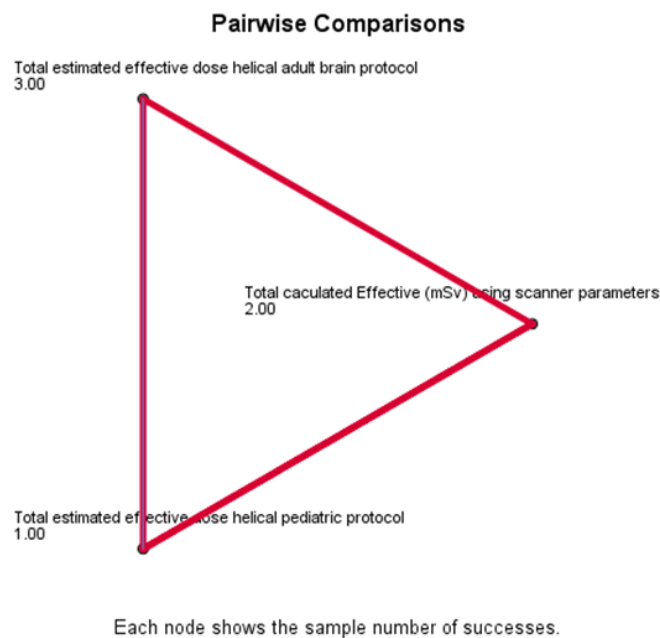


Figure 4.19: Pairwise Comparisons for Effective Dose Methods (Group 3, n=4).

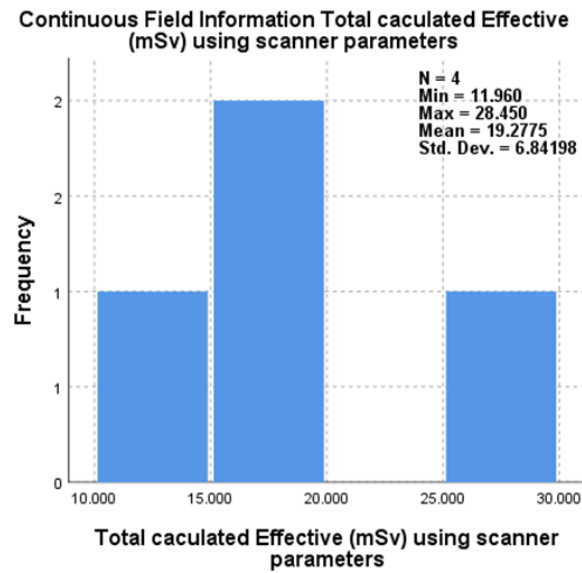


Figure 4.20: Distribution of Total Calculated Effective Dose (mSv) - Group 3 (n=4)

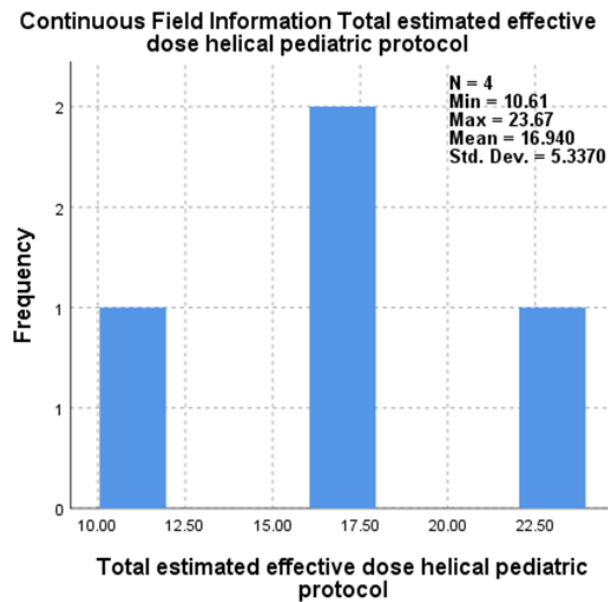


Figure 4.21: Distribution of Total Estimated Effective Dose (Pediatric Protocol) - Group 3 (n=4).

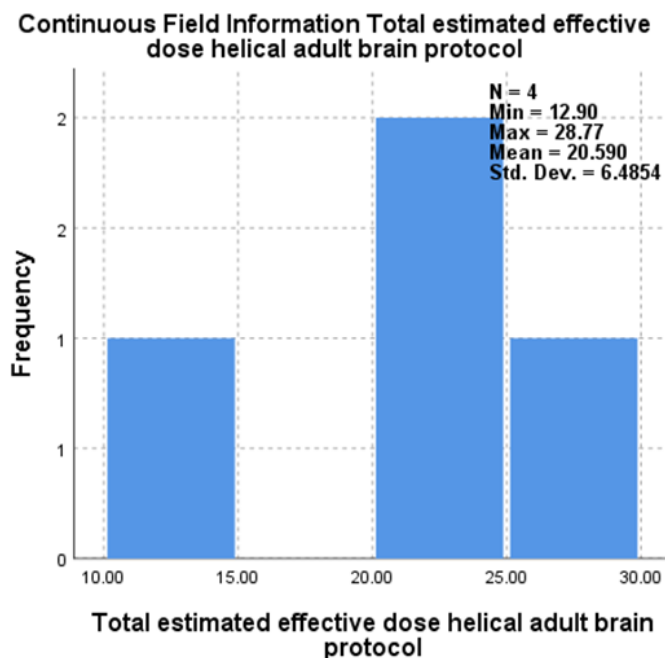


Figure 4.22: Distribution of Total Estimated Effective Dose (Adult Protocol) - Group 3 (n=4).

4.6 Summary of Dose Differences and Optimization Potential

The mean difference between the estimated pediatric protocol effective dose (1.27 mSv) and the scanner-calculated effective dose (1.46 mSv) was 0.19 mSv, according to the comparisons in Section 4.4 (Overall Sample). If clinical practice doses were in line with the optimal pediatric protocol, this would indicate a possible dose reduction of roughly 13% ($0.19 / 1.46$). On the other hand, the scanner-calculated effective dose was 0.08 mSv (about a 5.5% difference) lower than the estimated adult protocol effective dose (1.54 mSv), suggesting conducting awareness courses for physicians on how to request imaging studies appropriately.

Table 4.12: Summary of Mean Effective Dose Values (mSv) and Differences (Overall Sample).

Dose Method	Mean ED (mSv)	Difference from Calculated ED	% Difference from Calculated ED
Calculated (Scanner)	1.46	-	-
Estimated (Pediatric)	1.27	-0.19	-13.0%
Estimated (Adult)	1.54	+0.08	+5.5%

This indicates that there is a big chance to optimize dosage by using protocols that are more in line with pediatric standards.

Chapter Five: Discussion

5.1 Introduction

This chapter discusses the findings of the present study in relation to its main objectives and places them within the context of previous regional and international research. The primary aim was to determine whether the effective dose reported by CT scanners for pediatric brain examinations is more consistent with pediatric or adult-based dose estimation models. In addition, the study examined how technical parameters, including kVp, mAs, CTDIvol, DLP, and scan length, changed across repeated examinations and how these variations influenced cumulative radiation exposure. Finally, this chapter offers detailed clinical interpretations, safety implications, study strengths and limitations, comprehensive recommendations, directions for future research, and concluding remarks.

The findings showed a clear lack of systematic dose optimization methodology across all patient groups, a consistent and alarming pattern of rising radiation doses, and a significant protocol deviation toward adult-like technical settings. Of the 68 children in the sample, 73.5% were infants under one year, and this pattern was most noticeable among them, with the remainder being under two years. This age distribution is clinically important, as infants represent the most radiosensitive pediatric subgroup due to their rapid cellular division, small body size, and long remaining lifespan during which radiation induced effects may manifest.

Similar age distributions have reported in pediatric neuroimaging studies worldwide. For example, a study analyzing 308 CT scans in children younger than three years found that 70% of examinations performed in infants under one year of age, highlighting the predominance of this highly radiosensitive age group in pediatric neuroimaging. In that study, subdural effusions and hydrocephalus were among the most frequently identified

findings, reinforcing the role of CT as a frontline imaging modality for acute and congenital neurological conditions in early infancy (Bem et al., 1989).

This age group's majority heightens the clinical significance of the dose patterns observed in this study. This is especially important in Palestine; resource constrained medical setting, where risks increased by a lack of localized (DRLs), equipment limitations, and gaps in technician training. These findings offer a vital evidence-based basis for developing standardized, safe pediatric CT procedures that are adapted to regional circumstances.

5.2 Discussion of Major Findings

5.2.1 Scanner-Reported Effective Dose versus Pediatric and Adult Reference Estimates

One of the most important findings of this study is that the scanner-reported effective dose (mean 12.33 mSv) was statistically closer to the dose estimated using adult conversion factors (mean 13.04 mSv) than to the pediatric-based estimate (mean 10.73 mSv). This difference was highly significant and consistently observed across patient groups.

Two explanations may account for this finding. First, many CT scanners rely on internal dose calculation algorithms based on standard phantoms, which may not fully reflect the smaller head size and tissue composition of infants. Second, and more plausibly, the applied clinical protocols themselves appear to resemble adult scanning parameters. The latter interpretation is supported by the observed trends in kVp, mAs, and CTDIvol reported in Chapter Four, and aligns closely with findings from studies in Jordan and Saudi Arabia, where pediatric head CT doses were found to closely approximate adult values due to protocol drift and limited technologist training (Almujally et al., 2022; Rawashdeh et al., 2019).

This concern is further substantiated by the multicenter study, which analyzed 1,248 pediatric head CT examinations across 12 Jordanian hospitals and reported infant DLP values up to 550.9 mGy·cm, with two- to three-fold inter-hospital variability attributed to poor protocol standardization. The authors consequently proposed a national DRL of 409 mGy·cm, a benchmark that remains substantially lower than the mean DLP of 624.09 mGy·cm observed in the present study and well above European DRLs (300 mGy·cm), underscoring a clear need for standardized, pediatric-specific CT dose optimization (Hamedat et al., 2025).

Importantly, the pediatric-based estimated effective dose was approximately 13% lower than the scanner-reported value. This substantial difference demonstrates that proper implementation of age- and size-appropriate pediatric standard protocols, combined with necessary modifications to technical parameters when clinically indicated, could achieve meaningful radiation dose reductions. Comparable dose reductions have been demonstrated in international studies when pediatric-specific protocols are properly implemented (Kalra et al., 2015). For infants, even modest reductions are clinically meaningful, as cumulative exposure begins early in life and contributes to long-term stochastic risk (Brenner & Hall, 2007).

5.2.2 Variations in Scan Length and Their Impact on Radiation Dose

A prominent and concerning finding of this study was the variation in scan length or z-axis coverage between repeated examinations for the same patient, even when scans performed within very short time intervals. This variation underlying issues with scan planning and execution, and significantly increased overall exposure levels. The scan range determination appears to be very inconsistent between technologists and even between repeated examinations of the same patient, as it primarily depends on initial scout (tomogram) images.

In several cases, scan length increased by approximately 2 cm within 24 hours. Such changes cannot be explained by physiological growth, as normal infant linear growth is measured over weeks rather than days, which averages 2.5 cm per month during the first six months of life and slows to 1.3 cm per month between 7 and 12 months of age (Graber, 2023). Similar inconsistencies in cranio-caudal coverage have been identified by another study which reported that operator-dependent scan planning is a major contributor to unnecessary pediatric radiation exposure (Lin et al., 2023).

Because DLP is directly proportional to scan length, even small extensions of the scanned region result in measurable dose increases. A recent study in Ghana demonstrated that excluding redundant scan lengths in pediatric CT head protocols reduced DLP by approximately 7-11% without loss of clinical information, emphasizing the importance of strict scan range control as a simple but effective optimization strategy (Ampofo et al., 2025). In the present study, inconsistent scan length selection appears to reflect variable patient positioning, uncertainty in defining anatomical landmarks in infants, and a lack of standardized follow-up protocols.

5.2.3 Changes in Technical Parameters across Repeated Examinations

Across the three patient groups, exposure parameters such as mAs and CTDIvol demonstrated either stability without reduction or random fluctuation, rather than systematic dose optimization.

In Group 1 (two scans), This largest patient group showed high consistency in technical parameters between the initial diagnostic scan and the second follow-up scan, with no statistically significant changes observed in mAs (mean increase from 277.4 to 298.8), kVp (mean shift from 107.9 to 109.8), CTDIvol, DLP, or scan length (all p-values > .20). While parameter stability might seem positive, this consistency actually represents a major missed opportunity for radiation dose reduction during follow-up scans in pediatric head CT that are frequently performed for reasons such as postoperative assessment and shunt control, which often do not typically require the same image quality as initial diagnostic scans.

According to optimization studies, standard cranial CT protocols prioritize high image quality and conservative exposure settings, which may be unnecessary for focused imaging objectives. Significant dose reductions, particularly in tube voltage and current, can reduce surface dose by approximately 40% while maintaining adequate image quality for high-contrast tasks (Cohnen et al., 2000). However, the lack of systematic parameter reduction between initial and follow-up scans suggests that specific pediatric protocol adaptations and ALARA principles not effectively implemented, despite evidence of feasibility and safety.

In Group 2 (Three CT Scans, n = 6), the statistical analysis revealed significant variability in technical parameters (Friedman $\chi^2(14) = 77.40$, p < .001). However, after applying the Bonferroni correction for multiple comparisons, subsequent pairwise analyses revealed that almost none of the observed differences were statistically significant. The changes appeared random rather than resulting from systematic protocol adjustments, and there was no consistent dose reduction trend between subsequent scans.

In Group 3 (Four CT Scans, $n = 4$), the variations in scanning parameters across serial examinations remained statistically significant (Friedman $\chi^2(19) = 70.22/70.215$, $p < .001$). However, similar to the findings in Group 2, pairwise comparisons revealed no consistent or statistically significant differences between individual scan parameters after Bonferroni correction. The observed parameter changes were inconsistent, small in magnitude, and appeared to be driven more by technologist preferences than by systematic clinical considerations or protocol guidelines. In many cases, technical parameters increased rather than decreased in subsequent scans, resulting in progressively higher cumulative radiation exposure.

The observed changes in scan parameters between the initial and follow-up CT examinations for the same pediatric patient across all groups were not associated with a consistent dose optimization strategy. Instead, parameter adjustments were either minimal or inconsistent, suggesting reliance on default or technician-dependent settings rather than deliberate protocol modification. This finding is consistent with prior work by (LaQuaglia et al., 2021), who evaluated pediatric patients undergoing more than one head CT examination and demonstrated that when follow-up scans were performed using different protocols, particularly in pediatric-focused centers, significant reductions in radiation dose indices such as CTDIvol were achieved compared with the initial scans. Their results highlight that meaningful dose reduction in serial pediatric CT imaging is feasible when scan parameters are appropriately modified between examinations. In contrast, the lack of systematic parameter reduction observed in the present cohort indicates a missed opportunity for radiation dose optimization in follow-up scans, potentially contributing to unnecessary cumulative radiation exposure in pediatric patients.

5.2.4 Number of Examinations and Cumulative Dose

A statistically significant positive correlation was identified between the number of CT examinations and cumulative effective dose ($r = 0.250$, $p < 0.05$). This finding is consistent with a previous epidemiological study demonstrating that repeated CT exposure in childhood is associated with increased lifetime risks of leukemia and brain tumors (Pearce et al., 2012). The effect is particularly concerning in infants, as exposure begins early and accumulates over time.

Studies focusing on follow-up imaging in conditions such as hydrocephalus and traumatic brain injury have questioned the necessity of routine repeat CT scans, especially when clinical status is stable (Appelbaum et al., 2020) and there is a study that was able to reduce the need to repeat the image in children's head injuries from 29% to 20%, thus reducing their unnecessary radiation exposure (Jennings et al., 2017). The present findings suggest that, in the absence of clear justification and dose adjustment, repeated imaging contributes substantially to avoidable cumulative exposure.

5.2.5 Comparison with Diagnostic Reference Levels and Previous Studies

When the 75th percentile of CTDIvol (51.7 mGy) and DLP (1029.7 mGy·cm) compared with published European DRLs, both values were found to be considerably higher. These findings highlight the urgent need to review and optimize CT protocols in our hospitals to reduce radiation exposure for this vulnerable pediatric population (European Commission, 2014).

In comparison with regional studies, these results are consistent with, and in some cases worse than, findings from regional studies. For example, a study in Saudi Arabia reported dose escalation due to the use of adult presets for pediatric patients (Almujally et al., 2022). Similarly, a study in Jordan highlighted major mismatches when adult-based protocols

applied to children. Our study reinforces the systemic nature of this issue in the region (Rawashdeh et al., 2019).

However, these findings align with regional trends, but with variation. While a recent study from Abu Dhabi suggested a DRL level for DLP of 304 mGy·cm (Abulail et al., 2023), a Saudi study identified a higher value of 404 mGy·cm for the same age group (Alhailiy et al., 2023). Our study's values exceeding 600 mGy·cm suggest that practices in Palestine may be less optimized compared to major medical centers in Gulf countries that have begun implementing dose reduction strategies.

Comparison with international literature, Studies from distant countries emphasize dose reduction in pediatric CT. For example, a study demonstrated achievable dose reductions of 10 to 20% by lowering kVp and adjusting mAs (Kalra et al., 2015). The persistence of high doses in our context highlights a significant gap between international best practices and local implementation, especially compared to facilities with dedicated pediatric imaging centers. Another study also highlighted the clinical risks of repeated scanning, especially in cases requiring frequent monitoring, such as hydrocephalus or traumatic brain injury follow-up, where cumulative doses can go over safe reference levels (Yoshitake et al., 2020).

These results highlight the urgent clinical and public health necessity for systematic review, optimization, and standardization of CT protocols across Palestinian hospitals to reduce radiation exposure for this uniquely vulnerable population.

5.3 Clinical and Technical Interpretation

The elevated radiation doses observed among Palestinian pediatric patients likely reflect systemic reliance on adult-equivalent technical parameter settings instead of properly optimized, age- and size-specific pediatric protocols, significant equipment limitations including the complete absence of advanced dose modulation techniques such as ATCM, high random variability in scan length determination and technician-driven mAs selection, the frequent performance of scans without clear documented clinical justification in some cases, and the systematic overshooting of established international DRLs across multiple dose descriptors (European Commission, 2014).

However, recent research from 2022 to 2025 shows that newer techniques like Deep Learning Reconstruction (DLR) can reduce the dose by up to 71% while maintaining or improving image quality (Koetzier et al., 2023). The absence of such techniques in the studied environment exacerbates the problem, but also highlights the potential for massive dose reductions in the future upon adoption of these technologies.

5.4 Implications for Pediatric Radiation Safety

The comprehensive study results indicate several crucial insights for pediatric radiation safety practice. Current dose levels across all technical parameters consistently exceed clinically necessary thresholds, clearly demonstrating significant room for improvement through better monitoring, protocol standardization, and technician training. Infants face disproportionately high and largely preventable radiation risks due to their unique biological vulnerabilities. Implementing true evidence-based pediatric protocols, rather than approximations derived from adult protocols, could achieve dose reductions of 13% depending on the specific technical adjustments implemented. Most importantly, these findings underscore the public health imperative to establish national Palestinian Diagnostic DRLs to provide concrete benchmarks for quality control and dose optimization across all imaging facilities.

5.5 Conclusion

This comprehensive study conclusively demonstrates that infants undergoing head computed tomography (CT) scans in Palestine receive radiation doses significantly higher than international pediatric recommendations. The effective doses reported by the imaging device (averaging 12.33 mSv) were found to be more in line with adult protocol estimates (13.04 mSv) than with the true pediatric reference standard (10.73 mSv). Technical parameters, including voltage (kVp), current (mA), volumetric CT dosing index (CTDIvol), radiation dose per lead (DLP), and scan length, showed no evidence of systematic optimization across sequential scan sets, resulting in unnecessary cumulative radiation exposure, often reaching dangerously high levels of 30–40 mSv or more.

The 75th percentile values of CTDIvol and DLP exceeded the published European DRLs for the corresponding pediatric age groups. These results confirm that the application of standardized, evidence-based pediatric protocols can achieve immediate and substantial radiation dose protection for this vulnerable age group, reducing the mean dose by approximately 13%, with the potential for further improvements. With the emergence of advanced technologies such as deep learning reconstruction (DLR), which promises even greater dose reductions, it is crucial that Palestine adopts these innovations. The findings collectively underscore the need for a comprehensive overhaul of national protocols, enhanced training for technicians, the establishment of diagnostic reference levels specific to Palestine, and systematic quality improvement initiatives to ensure safer imaging practices for children throughout the country.

5.6 Study Strengths

This study exhibits several important methodological strengths that enhance its scientific validity and practical utility. It represents the first Palestinian study to date specifically addressing radiation dose patterns in serial pediatric CT scans, providing essential baseline data that was previously unavailable.

The study employed a rigorous triple-dose comparison methodology between scanner-calculated values and pediatric and adult protocol estimates using standardized phantom scanning techniques. The comprehensive multi-parameter technical analysis included a systematic evaluation of changes in mAs, kVp, CTDIvol, DLP, and scan length across serial examinations. Crucially, this study is the first Palestinian study to demonstrate and quantify the systematic drift of radiation dose toward adult exposure levels when imaging children. Collectively, these rigorous methods provide a solid, evidence-based foundation for the development of future national DRLs and optimization protocols specific to the Palestinian healthcare context.

5.7 Study Limitations

Despite its strengths, this study has several important limitations that must be acknowledged. The sample size remained relatively modest ($n=68$ total across three groups) and was derived entirely from a single hospital site, which may limit the generalizability of the findings to other Palestinian facilities with different equipment or practice patterns. Variations in scanner calibration between different institutions could affect the accuracy of absolute dose comparisons. In the absence of established local Palestinian DRLs, the reliance on international European benchmarks may not perfectly reflect optimal local reference values.

The retrospective design of the study precluded a thorough assessment of the clinical justification for repeat scanning or a detailed evaluation of the decision-making processes of referring physicians. Image quality was not systematically assessed against dose levels, leaving uncertainty regarding potential diagnostic trade-offs from dose reduction strategies. Finally, the limited availability of previous local Palestinian comparative data restricted the contextualization of the findings against national trends.

5.8 Clinical and Public Health Implications and Recommendations

The study findings highlight the critical necessity for a thorough revision of Palestine's pediatric CT imaging procedures, along with a number of concrete and useful suggestions:

- Establishment of national protocols for CT scans for children and made mandatory, specifying low values for kVp and current mAs, as well as a precise determination of the scan length calibrated according to the patient's age, weight, and size.
- Establishing ongoing training programs for technicians and physicians on consistent planning of screening images, improving technical standards for pediatric patients, and adhering to the principles of minimizing radiation exposure (ALARA).
- Strict clinical justification requirements must be applied to each computed tomography scan, with particular scrutiny of repeat scans, to ensure that ionizing radiation is only used when the clear diagnostic benefit outweighs the risks of radiation.
- Urgent development of Palestinian National DRLs through multi-center collaborative studies, to provide standardized and locally appropriate criteria for radiation dose optimization and patient safety monitoring in all imaging facilities.

- The gradual adoption of modern CT techniques, ATCM and iterative reconstruction algorithms, to achieve lower doses without compromising diagnosis.

5.9 Future Research Directions

While this study provides essential baseline data for pediatric CT practices in Palestine, several critical areas require further investigation:

- Prospective, multicenter studies in Palestinian hospitals to establish reliable national diagnostic reference standards.
- Image quality-to-dose trade-off analysis using objective measures (contrast-to-noise ratio, signal-to-noise ratio).
- Review of the clinical rationale for repeat imaging in chronic neurological diseases.
- Training trials for interventional radiology technicians to measure sustained dose reduction.
- Evaluative studies on the impact of deep learning image reconstruction techniques in resource-limited settings to assess their feasibility and dose reduction effect.
- Long-term epidemiological studies to follow patients exposed to high cumulative doses (>30 mSv).
- Comparative studies between MRI and CT for non-emergency pediatric neuroimaging.

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Appendices:

Appendix A: IRB Approval

<i>Arab American University</i> Institutional Review Board - Ramallah		الجامعة العربية الأمريكية مجلس أخلاقيات البحث العلمي - رام الله
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IRB Approval Letter

Study Title: "Radiation Dose Evaluation for Pediatric Patients Undergoing Repeated Brain Computed Tomography Examination: A Retrospective Study".

Submitted by: Noor Jamal Abuasbi

Date received:	16 th June 2024
Date reviewed:	23 th June 2024
Date approved:	30 th June 2024

Your Study titled "Radiation Dose Evaluation for Pediatric Patients Undergoing Repeated Brain Computed Tomography Examination: A Retrospective Study" with the code number "R-2024/A/113/N" was reviewed by the Arab American University Institutional Review Board - Ramallah and it was approved on the 30th of June 2024.

Sajed Ghawadra, PhD
IRB-R Chairman
Arab American University of Palestine





General Conditions:

1. Valid for 6 months from the date of approval.
2. It is important to inform the IRB-R with any modification of the approved study protocol.
3. The Bord appreciates a copy of the research when accomplished.

Tel: 02-294-1999	رام الله - فلسطين E-Mail: IRB-R@aaup.edu	Website: www.aaup.edu
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Appendix B: MOH Approval

State of Palestine Ministry of Health Education in Health and Scientific Research Unit		دولة فلسطين وزارة الصحة وحدة التعليم الصحي والبحث العلمي
Ref.: Date: الرقم: ٢٠٢٠/١٦٨٥/ج التاريخ: ٢٠٢٠/١١/١٨ الأخ مدير عام الادارة العامة للمستشفيات المحترم،،، الاخـت رئيس وحدة التخطيط والسياسات الصحية المحترمة،،، عطوفة الوكيل المساعد للمهن المساندة وبنوك الدم المحترم،،، تحية واحترام،،، <u>الموضوع: تسهيل مهمة بحث</u> يرجى تسهيل مهمة الطالبة: نور جمال عبد الله ابو عصبه - ماجستير برنامج علم الم والمناعة- الجامعة العربية الامريكية، لعمل بحث بعنوان: تقييم جرعة الاشعة للمرضى الأطفال الذين يخضعون لتصوير الدماغ المقطعي المتكرر: دراسة بأثر رجعي" حيث ستقوم الطالبة بجمع معلومات من ملفات المرضى وذلك في: • مستشفى رفيديا مع العلم ان مشرفة البحث: د. محمد الجمل. على ان يتم الالتزام بالمحافظة على اخلاقيات البحث العلمي وسرية المعلومات، وعدم التعرض للمعلومات التعريفية للمشاركين. على ان يتم تزويد الوزارة بنسخة PDF من نتائج البحث، التعهد بعدم النشر لحين الحصول على موافقة وزارة الصحة. مع الاحترام،،،  د. عبد الله القواسمي رئيس وحدة التعليم الصحي والبحث العلمي نسخة: عميد كلية الدراسات العليا المحترم/ الجامعة العربية الامريكية		
Telfax.: 09-2333901 scientificresearch.dep@gmail.com تلفاكس: 09-2333901		

الملخص

المقدمة:

غالبًا ما يحتاج الأطفال المصابون بأمراض عصبية إلى فحوصات تصوير مقطعي محوسب متكررة، مما يثير القلق بشأن الآثار طويلة المدى للتعرض المتراكم للإشعاع. ونظرًا لوجود اختلافات في الممارسات السريرية، أصبح من الضروري تحسين بروتوكولات التصوير المقطعي.

هدف الدراسة:

تهدف هذه الدراسة إلى: (1) مقارنة الجرعات المسجلة والمحسوبة من الجهاز مع التقديرات المستندة إلى بروتوكولات قياسية للأطفال والبالغين، (2) تحليل التغيرات في معايير الفحص بين مجموعات المرضى المختلفة، (3) تقييم قيم مؤشر الجرعة في التصوير المقطعي، وطول المسار الجرعي، والجرعة الفعالة لدى الأطفال الذين خضعوا لفحوصات دماغية متكررة، و(4) استكشاف فرص تحسين البروتوكولات بما يحقق خفض الجرعة الإشعاعية.

منهجية الدراسة:

أُجريت هذه الدراسة الاسترجاعية على (68) طفلًا خضعوا لفحوصات دماغية باستخدام التصوير المقطعي المحوسب بمعدل يتراوح بين فحصين وأربعة فحوصات، وذلك في مستشفى ريفيدا الجراحي خلال الفترة من عام 2021 حتى عام 2024. تم جمع البيانات الخاصة بمعايير الفحص المسجلة من الجهاز، كما استُخدمت التحليلات الإحصائية المناسبة (اختبار الارتباط، اختبار فريدمان، والاختبارات الزوجية) لمقارنة مؤشرات الجرعة، ودراسة التغيرات بين المجموعات المختلفة، وتحليل العلاقات بين المتغيرات

النتائج:

أظهرت نتائج الدراسة أن الجرعة الإشعاعية الفعّالة الكلية ازدادت مع زيادة عدد الفحوصات. كما تبين وجود فروق ذات دلالة إحصائية ($p < 0.001$) بين الجرعات المحسوبة من الجهاز وتلك المقدّرة وفق بروتوكولات الأطفال والبالغين. وبَيّنت النتائج أن الجرعات السريرية الفعلية كانت أقرب إلى التقديرات الخاصة ببروتوكولات البالغين مقارنة ببروتوكولات الأطفال. وتشير التحليلات إلى إمكانية تقليل الجرعة بنحو (13%) عند الالتزام الأمثل ببروتوكولات الأطفال

الاستنتاج:

تُظهر الدراسة أن فحوصات الدماغ المتكررة للأطفال باستخدام التصوير المقطعي المحوسب قد تؤدي إلى زيادة ملحوظة في الجرعة الإشعاعية، خاصة بعد الفحص الثاني. كما يتضح أن الممارسة الحالية تعتمد في كثير من الأحيان إعدادات أقرب إلى بروتوكولات البالغين بدلاً من بروتوكولات الأطفال، مما يستدعي الالتزام الصارم بالبروتوكولات المحسّنة للأطفال، مع ضرورة تبرير كل فحص ومراجعة معاييرها بدقة لضمان تقليل التعرض الإشعاعي قدر الإمكان لدى هذه الفئة الحساسة

الكلمات المفتاحية:

التصوير المقطعي المحوسب للأطفال، تصوير الدماغ، الفحوصات المتكررة، الجرعة الإشعاعية، الجرعة الفعّالة، مؤشر الجرعة في التصوير المقطعي، طول المسار الجرعي، تحسين بروتوكولات الفحص، الحماية من الإشعاع.