# EVALUATION OF RADIATION DOSE FOR COMMON COMPUTED TOMOGRAPHY ASSESSMENT IN NORTH OF JORDAN

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**by**

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| | |
|---|---|
| CT | Computed Tomography |
| CTDI | CT dose index |
| CTDIvol | CT dose index volumetric |
| DLP | Dose length product |
| DRL | Diagnostic Reference Level |
| ICRP | International Commission on Radiological Protection |
| IRB | Institutional Review Board |
| kV | kiloVolts |
| kVp | kiloVolt peak |
| LAR | Lifetime Attributable Risk |
| M | Mean |
| mAs | Milliampere-Seconds |
| mGy | milliGray |
| mSv | millisievert |
| NCRP | National Council on Radiation Protection and Measurements |
| NRPB | National Radiation Protection Board |
| PMMA | Polymethylmethacrylate |
| SSDE | Size specific dose estimate |
| SD | Standard deviation |

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# PENILAIAN DOS SINARAN UNTUK PEMERIKSAAN TOMOGRAFI KOMPUTER UMUM DI UTARA JORDAN

## ABSTRAK

Peningkatan penggunaan tomografi berkomputer (CT) memerlukan penilaian yang teliti terhadap pendedahan radiasi dan risiko kanser yang berkaitan. Kajian ini menyiasat risiko kanser yang boleh dikaitkan dengan jangka hayat (LAR) akibat pendedahan radiasi dalam imbasan CT yang biasa dan menganalisis variasi dos mengikut protokol pengimbas. Menggunakan model Linear Non-Threshold (LNT) BEIR VII dan perisian simulasi Monte Carlo VirtualDose™, dos organ dan dos efektif telah dianggarkan, dan Tahap Rujukan Diagnostik (DRL) telah dicadangkan untuk mengoptimumkan dos radiasi di Jordan. Keputusan kajian menunjukkan penurunan LAR seiring dengan peningkatan umur, dengan risiko tertinggi dilihat pada pesakit muda (18–19 tahun), terutamanya untuk kanser paru-paru (71 lelaki dan 124 perempuan bagi setiap 100,000 imbasan). Secara umumnya, wanita menunjukkan LAR yang lebih tinggi berbanding lelaki. Purata dos otak adalah 14.20 mGy, manakala dos efektif berkisar antara 1.74 hingga 3.08 mSv. Dos paru-paru lebih tinggi pada lelaki (24.51 mGy) berbanding perempuan (10.81 mGy), manakala wanita menerima dos yang sedikit lebih tinggi untuk perut, kolon, dan hati. Indeks Dos Tomografi Volumetrik (CTDIvol) dan Produk Panjang Dos (DLP) menunjukkan variasi yang ketara di kalangan model pengimbas, dengan pengimbas GE dan Siemens (64-lapis) menunjukkan nilai yang lebih rendah berbanding pengimbas Toshiba. DRL Jordan ditemui lebih tinggi berbanding dengan piawaian antarabangsa, yang menunjukkan keperluan untuk pengoptimuman dos. Penemuan ini menekankan pentingnya penubuhan DRL yang disesuaikan dengan amalan tempatan untuk meningkatkan keselamatan radiasi dan mengurangkan risiko kanser, terutamanya untuk populasi yang terdedah seperti pesakit muda dan wanita. Penyeragaman protokol dan latihan khusus untuk jururadiograf dapat mengatasi variasi dos di kalangan hospital dan pengimbas. Kajian ini menekankan keperluan untuk pengoptimuman berterusan dan protokol pencitraan yang berfokuskan pesakit untuk meningkatkan hasil klinikal dan keselamatan pesakit.

# EVALUATION OF RADIATION DOSE FOR COMMON COMPUTED TOMOGRAPHY ASSESSMENT IN NORTH OF JORDAN

## ABSTRACT

The increasing use of computed tomography (CT) necessitates careful evaluation of radiation exposure and associated cancer risks. This study investigates the lifetime attributable risk (LAR) of cancer from radiation in common CT scans and analyzes dose variations across scanner protocols. Using the BEIR VII Linear Non-Threshold (LNT) model and VirtualDose™ Monte Carlo simulation software, organ and effective doses were estimated, and Diagnostic Reference Levels (DRLs) were proposed to optimize radiation doses in Jordan. Results showed a decrease in LAR with age, with the highest risks observed in younger patients (18–19 years), especially for lung cancer (71 males and 124 females per 100,000 scans). Females generally exhibited higher LAR than males. Average brain doses were 14.20 mGy, while effective doses ranged from 1.74 to 3.08 mSv. Lung doses were higher in males (24.51 mGy) compared to females (10.81 mGy), while females received slightly higher doses for the stomach, colon, and liver. The CT Dose Index volumetric (CTDIvol) and Dose Length Product (DLP) varied significantly across scanner models, with GE and Siemens (64-slice) scanners showing lower values compared to Toshiba scanners. Jordanian DRLs were found to be higher than compared international studies, indicating the need for dose optimization. These findings underscore the importance of establishing DRLs tailored to local practices to enhance radiation safety and reduce cancer risks, particularly for vulnerable populations such as younger and female patients. Standardizing protocols and providing targeted radiographer training can address dose variability across hospitals and scanners. The study emphasizes the need for continuous optimization and patient-centered imaging protocols to improve clinical outcomes and patient safety.

# CHAPTER 1

# INTRODUCTION

## 1.1 Introduction

Since its introduction in the 1970s, computed tomography (CT) has become a cornerstone of diagnostic medicine, enabling accurate visualization of internal anatomy and the diagnosis of conditions previously undetectable (Bardo and Brown, 2008; Cho, 2013; Khatonabadi et al., 2013). The advent of multi-slice CT (MSCT) technology in 1992, with machines now capable of up to 320 slices, has further revolutionized radiological diagnostics by offering rapid, high-resolution imaging (Omori and Schajer, 2023). Chest CT, for instance, is preferred over conventional radiography for detecting lesions and other abnormalities (Yang et al., 2017).

The global use of CT scans has grown dramatically, with approximately 400 million scans performed annually worldwide, equating to 55 scans per 1,000 people (Mahesh et al., 2022). In the United States alone, over 70 million CT scans are conducted yearly, contributing to their widespread adoption in emergency and outpatient settings (Zacharias et al., 2013; Almohiy, 2014; Goske et al., 2014; Geyer et al., 2016). Despite their diagnostic benefits, CT scans account for a significant proportion of radiation exposure in medical imaging, comprising only 12% of imaging investigations but over half of the cumulative dose to the public (Mettler Jr et al., 2020).

The increased use of CT raises concerns about radiation risks, including deterministic effects and stochastic effects such as radiation-induced cancer(Garba et al., 2021). CT delivers relatively high radiation doses (10–100 mGy per scan) compared to other imaging modalities, prompting calls for optimization to protect patients, especially vulnerable populations such as children and young adults (ICRP, 2017). Epidemiological data, including studies of Hiroshima atomic bomb survivors, indicate that even low levels of radiation exposure can increase cancer risk (Saenko and Mitsutake, 2024). In the United States, it is estimated that CT scans contribute to 29,000 new cases of radiation-induced cancer annually (Goske et al., 2014).

Efforts to mitigate these risks include the application of the ALARA (As Low As Reasonably Achievable) principle, which seeks to reduce radiation exposure while maintaining diagnostic image quality. Diagnostic Reference Levels (DRLs) serve as a critical tool in optimizing CT protocols, guiding radiographers and clinicians in balancing diagnostic efficacy with patient safety (ICRP, 2017).

CT provides rapid, accurate three-dimensional data and a manageable model (Liang et al., 2017b), CT procedures provide visualization of the internal anatomic structure of the human body and diagnosis of many diseases that were previously undiagnosable, and Chest CT is the preferred method for lesion detection over conventional chest radiography.

A growing number of CT scans have been performed globally because they need less time and are less costly to diagnose, but the high levels of patient dose they produce have generated concerns in many nations (Zenone et al., 2012; Power et al., 2016). These days, imaging technology, especially computed tomography, is essential for the correct diagnosis of many disorders (CT).

This study aims to raise awareness of radiation risks and optimize imaging protocols. Also, this study provides valuable information for radiologists, medical professionals, and patients in the region to make informed decisions about the use of CT scans for diagnostic purposes. Also, this study intends to set DRLs for common

CT examinations, in the north of Jordan, based on CTDIvol and DLP, similar to methods used in International DRLs. Also, this study aims to provide valuable information for radiologists, medical professionals, and patients in Jordan to make informed decisions about the use of CT scans for diagnostic purposes.

## 1.2 Problem Statement

CT is a widely used imaging modality that enables detailed visualization of internal organs and structures. However, CT exposes patients to ionizing radiation, which can increase the risk of radiation-induced cancer. While international studies have documented the magnitude of radiation exposure and associated cancer risks, there is limited research in Jordan, and no studies have specifically examined the radiogenic cancer risk associated with CT scans. This lack of data presents significant challenges for medical professionals and authorities in Jordan, who must balance the diagnostic benefits of CT against its potential risks (Alhasan et al., 2016).

Globally, CT usage has increased rapidly, with studies confirming that CT scans deliver higher radiation doses compared to other imaging modalities (Smith-Bindman et al., 2015). For example, patients undergoing multiple CT examinations have been shown to face elevated cancer risks, with studies reporting 6.8% of cancer-related deaths linked to repeated CT exposures (Cao et al., 2022). Additionally, CT dosimetry studies have revealed a wide range of effective dose (ED) values for various procedures, such as 0.3–8.2 mSv for brain CT examinations (Okonkwo et al., 2022). Repeated exposures are a concern, with 39% of patients receiving cumulative radiation doses from multiple brain CT scans (Mettler Jr et al., 2020).

To address these risks, the International Commission on Radiological Protection (ICRP) introduced the concept of effective dose (ED) to quantify the hazards of non-uniform radiation exposure based on tissue radiosensitivity (ICRP, 2017). The ICRP and the International Atomic Energy Agency (IAEA) emphasize the need to optimize CT usage by minimizing radiation exposure without compromising image quality (ICRP, 2017). One proven strategy to achieve this is the establishment of DRLs, which are benchmarks for optimizing medical imaging practices. DRLs enable comparisons of local data with international standards to reduce unnecessary radiation exposure.

Despite the global adoption of DRLs, there are few studies on CT practices in Jordan, leaving a gap in the optimization of radiation exposure for local patients. This study aims to address this gap by evaluating the effective dose and the risk of radiogenic cancer for adult patients undergoing brain, chest, and abdomen CT scans in Northern Jordan. Additionally, the study seeks to establish DRLs for these procedures, contributing to evidence-based decision-making and enhanced radiation safety in clinical practice.

## 1.3 Significant of Study

The significance of this study is to address the gap by enhancing understanding and awareness of radiation dose and cancer risk associated with CT scans. The findings will be instrumental in establishing dose guidelines and DRLs for common CT examinations performed in the Northern region of Jordan. Additionally, this study is significant for evaluating current clinical practices and optimizing radiation exposure in Jordan. Furthermore, it aims to improve dose management by reducing the frequency of unnecessary radiation exposure and proposing corrective methods to decrease radiation doses in the country.

## 1.4 Objectives

i) To evaluate the protocol for different CT scanner and show the factors contribute to variations in radiation exposure.

ii) To evaluate the radiation dose received by adult patients who underwent common CT scans by estimating the amount of effective radiation dose and organ dose then comparing the results between different CT scanner protocol in north of Jordan, as well as comparing the results with other studies.

iii) To determine the LAR estimation using BEIR VII, as well as comparing the results between different age group of male and female patients who underwent common CT examinations in the northern region of Jordan.

iv) To verify diagnostic reference level (DRL) for common CT examination in north of Jordan and to compare the findings with other studies.

## 1.5 Scope of Study

This study investigates the radiation dose and associated radiogenic cancer risks in CT procedures for brain, chest, and abdominal imaging in patients from the northern region of Jordan. The study utilizes retrospective patient data to calculate the effective radiation doses and evaluate the LAR of cancer. Patient demographics, including age, gender, and clinical history, were analyzed to assess the variations in radiation exposure and risk across different subgroups.

For dose estimation, the study used a VirtualDose™ software, which calculates organ-specific radiation doses based on scanner settings, patient anatomy, and exposure parameters. Specific focus is given to evaluating the mean dose differences between male and female patients, exploring potential clinical relevance and statistical significance. Moreover, the risks of developing cancer were analyzed by using international models to correlate radiation exposure with epidemiological data.

The study was designed to address critical aspects of radiation protection and dose optimization in CT imaging. However, the scope is limited to specific imaging protocols and patient populations. Other variables, such as variations in scanner technologies, scan techniques, and institutional practices, were not included in the analysis. Additionally, the study does not incorporate advanced imaging modalities like dual-energy or spectral CT. The investigation is confined to single-phase imaging protocols for the brain, chest, and abdomen, without evaluating multi-phase or contrast-enhanced imaging protocols.

The following limitations are recognized in this study:

1. The study utilized retrospective data from a specific geographic region, which may not fully represent the diversity of patient characteristics or imaging practices in other areas.
2. The analysis focused on mean organ doses and LAR of cancer; other metrics of image quality, such as contrast-to-noise ratio, spatial resolution, or dose optimization strategies, were not considered.
3. The study excluded pediatric and obese patient populations, limiting its applicability to adult patients with medium body sizes.
4. The weight and size of patient did not document in the hospitals participated in the study.

## 1.6 Thesis Outlines

The overall structure of this thesis takes the form of five chapters. Chapter 1 introduces the study by discussing the significance of radiation dose assessment and associated radiogenic cancer risks in computed tomography (CT) imaging. The problem statement, research objectives, and the scope of the study are detailed in sections 1.2, 1.3, and 1.4, respectively. Chapter 2 provides an extensive review of previous studies related to radiation dose estimation, cancer risk modeling, and the evaluation of CT imaging protocols. Chapter 3 focuses on the methodologies employed in this study. It describes the retrospective data collection process, the dosimetry tools used for organ-specific dose estimation, and the statistical analyses conducted to evaluate the differences in radiation exposure and lifetime attributable risk (LAR) of cancer. Chapter 4 presents the results of the study, highlighting the mean organ dose distributions and LAR of cancer for brain, chest, and abdominal CT scans. It includes a comparative analysis of dose variations between male and female patients and statistical significance tests performed on these differences. Finally, Chapter 5 summarizes the conclusions drawn from the research. It highlights the practical implications of the findings for dose optimization in CT imaging and provides recommendations for enhancing radiation safety practices.

# CHAPTER 2

# LITERATURE REVIEW

This chapter provides a critical overview about published works that are associated with the objectives and research problems of this research study. This chapter also explains the role of CT dosimetry in optimization of CT dose. The current practice of CT scan that are used in CT scan examinations are highlighted in this chapter. The role of DRL CT guidelines in enhancement techniques in CT imaging is also discussed at the end of this chapter.

## 2.1 The Use of X-rays in Medical Field

William Conrad Rontgen, a German physics professor at the University of Wurzburg, made the unexpected discovery of X-radiation on November 8, 1895. While he was in his laboratory in total darkness observing the glow in an evacuated cathode-ray tube caused by electric discharges, a fluorescent green screen coated with barium platinocyanide crystals (within range of the radiation emanating from the tube) began to glow. The fluorescent screen was used at the time to detect ultraviolet rays, since this Rontgen conclusion concludes that this new "ray" was being emitted from the evacuated tube and was able to pass through dense black paper to excite phosphorescent materials in the room, this "ray" stimulated phosphorescent materials in the room. After a series of studies, Rontgen observed that this light could pass through most stiff materials, but not human or animal bone or metal. His initial try consisted of an outline of his wife's hand skeleton on the screen (Lindell, 2019). Six months after its discovery, X-rays were utilized to uncover embedded bullets in injured soldiers, in 1901, the Nobel Prize, one of the earliest in history, was awarded in recognition of his accomplishments, technological advancements have enabled the production of smaller, lighter, and more transportable image-generating devices (Patel et al., 2023a).

The technique of taking X-ray images, which enables the study of a person's internal anatomy without the need for invasive surgery, swiftly gained the respect of physicians and expanded over the globe. In 1897, William Morton took the first X-ray image of a complete skeleton. This was the result of the rapid development of X-ray research, which began with the construction of machines for obtaining X-ray images for medical purposes. The architecture of X-ray equipment has been improved over time to produce more clearer two-dimensional images of the interior of the human body, it is extensively utilized for diagnosing conditions like fractures, foreign objects in the body, and even metal accumulations in tissues related to autoimmune diseases (Bazin et al., 2022). Furthermore, X-ray imaging, despite its challenges like image quality issues, benefits from image processing techniques for more accurate diagnostics, often employing machine learning methods (Gentile et al., 2020).

## 2.2 Computed Tomography

The origin of computed tomography (CT) can be traced back to the groundbreaking work of Sir Godfrey Hounsfield, who developed the first CT scanner in 1971 with the financial support of Electric and Musical Industries, Ltd (EMI) (Patel et al., 2023b). This innovative technology revolutionized medical imaging by allowing for the visualization of internal body structures in a non-invasive manner. Initially designed for head imaging, modern CT systems can now conduct full-body examinations rapidly, thanks to advancements in hardware, image reconstruction techniques, and computing power, see Figure 2.1 which show the modern CT scanner (Buzug, 2011; Mannil and Saltybaeva, 2020). CT scans involve the use of X-rays to create detailed cross-sectional images of organs, aiding in the diagnosis of various conditions such as tumors, strokes, and inflammatory processes (Ręba, 2021). The development of CT marked a significant milestone in medical imaging history, offering clinicians a powerful tool for accurate diagnosis and treatment planning (Duan et al., 2016). Recent advancements in musculoskeletal CT, such as 4-dimensional, cone-beam, and dual-energy techniques, have enhanced imaging capabilities for trauma, gout, and biomechanical assessments during motion and weight-bearing, CT scans are crucial in acute care, stroke, trauma, and oncology due to their ability to generate multi-planar images and contrast-enhanced imaging, aiding in accurate diagnosis and management (Lell and Kachelrieß, 2023). Continuous improvements in CT technology, including dose reduction, high temporal resolution for cardiac imaging, and the integration of photon-counting detectors, highlight the ongoing evolution and significance of CT in modern healthcare (Hampel, 2022).

Figure 2.1  CT scanner machine (Buzug et al, 2011).

CT scanners are a significant achievement in the fields of medicine, physics, and engineering. The first clinical CT scanner was obtaining one 80 * 80 transverse section in five minutes. CT images were created using translate-rotate geometry; two years after the introduction of the first EMI scanner, eight CT constructors utilizing a variety of scanning techniques to image the head and body were developed; and modern CT scanners can acquire 1200 512 * 512 transverse sections per second (Lell and Kachelrieß, 2023). In the 1980s, third-generation rotate-rotate geometry became the predominant technique, which is still utilized today (Lell and Kachelrieß, 2023). Lowering interscan delay time from 10 seconds (1980s) to 1-2 seconds (1990s) was the cornerstone of early CT, by designing spiral path using non-stop gantry rotation on a slip ring with unbroken table translation to provide the scan of the entire chest or abdomen in a single breath hold. With the introduction of greater scan pitch (9) and sub-second gantry rotation, scan time reductions continued throughout the 1990s (Lell and Kachelrieß, 2023)

In 1998, the four-detector row CT scanner had a significant impact on the CT system. Multidetector CT, which contributed to the development of 16–detector row CT in 2002 and 64–detector row CT in 2004, permitted the creation of retrospective electrocardiographically gated spiral scanning, which produced contrast-enhanced pictures of the heart and coronary arteries. In 2006, the introduction of a dual-source, dual-detector CT scanner with a temporal resolution of 83 milliseconds facilitated strong coronary artery imaging, thereby strengthening cardiac imaging. In 2010, a 16-cm-wide, 320-row detector system capable of imaging a single heartbeat with a stationary table was developed (Lell and Kachelrieß, 2023).

## 2.3 The Development of CT Scanning

The development of CT scanners has undergone a transformative journey, revolutionized medical imaging and impacted the diagnosis and treatment of various medical conditions. The journey of CT scanner development began with the invention of the first-generation CT scanner by Sir Godfrey Hounsfield in 1972 (Figure 2.2). These scanners utilized a single X-ray source and a single detector to obtain cross-sectional images. The primary innovation was the use of mathematical algorithms to reconstruct images from multiple X-ray projections. However, these scanners were slow and had limited clinical applications (Sera, 2021).

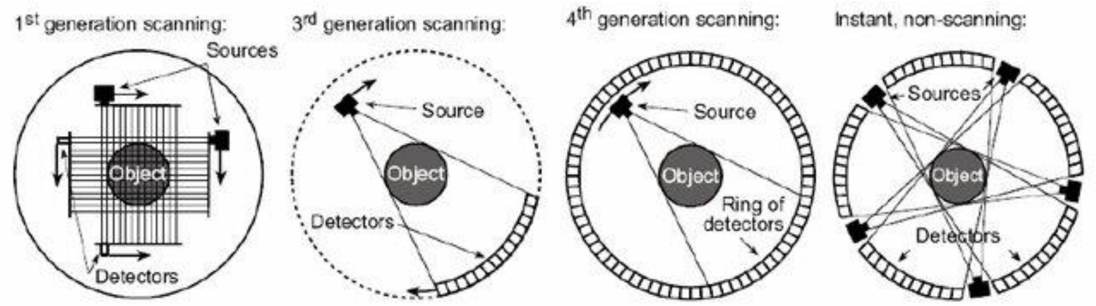

Figure 2.2 CT scanner generations (Ashraf, 2007).

The second-generation CT scanners, introduced in the late 1970s, brought a significant improvement with the introduction of fan beam technology. Fan beam scanners utilized multiple detectors and a rotating X-ray source to reduce scanning time and improve image quality. This generation marked a crucial step towards clinical feasibility (Sera, 2021). Third-generation CT scanners, developed in the early 1980s, further enhanced image quality and clinical utility. They featured a larger number of detectors, leading to improved spatial resolution and reduced scanning time. The introduction of helical or spiral scanning, allowing continuous table movement during scanning, opened up new possibilities in diagnostic imaging (Sera, 2021).

Fourth-generation CT scanners, introduced in the mid-1980s, featured curved detectors and a stationary X-ray source. These curved detectors allowed for improved image resolution and reduced scatter radiation, resulting in clearer images. This generation marked a significant advancement in image quality (Sera, 2021). Fifth-generation CT scanners, introduced in the late 1990s, revolutionized CT imaging. They featured the ability to acquire multiple slices (typically four) simultaneously, significantly reducing scan time and enhancing clinical throughput. This development enabled the rapid acquisition of high-quality images, particularly for cardiovascular and trauma patients (Sera, 2021). Sixth-generation CT scanners, which emerged in the early 2000s, pushed the boundaries of multi-slice capabilities. They could acquire up to 64 slices in a single rotation, allowing for high-resolution imaging of various anatomical regions. Additionally, dual-energy CT technology was introduced, enabling better tissue differentiation and material characterization (Sera, 2021). Seventh-generation CT scanners, introduced in the mid-2000s, brought further improvements in detector technology. These scanners featured more advanced detectors, often with a higher number of detector rows, allowing for even faster scanning and improved image quality. Spectral imaging capabilities, which enable the assessment of tissue composition, were also integrated into some models (Sera, 2021). Eighth generation and subsequent CT scanners represent the cutting edge of technology in medical imaging. These scanners offer ultra-high spatial resolution, reduced radiation dose, and advanced artificial intelligence (AI) capabilities. AI algorithms assist in image reconstruction, noise reduction, and the automation of routine tasks, thereby improving diagnostic accuracy and clinical efficiency (Morita et al., 2020).

## 2.4 CT Scan Modes

CT scanning, a versatile medical imaging technique, provides detailed cross-sectional views of the human body. The introduction of helical or spiral CT scanning in the early 1980s revolutionized the field. Helical CT, with continuous volume acquisition as the patient table moves smoothly during the scan, significantly reduced scan time. This innovation became the standard for clinical applications, enabling the reconstruction of multiple slices in a single rotation and enhancing the efficiency of CT imaging (Withers et al., 2021).

### 2.4.1 Conventional CT Scan Modes

The earliest CT scan modes involved single-slice imaging, where a single detector acquired data at a time. This method was time-consuming and less efficient. Sequential scanning, a slight improvement, involved moving the patient table incrementally between scans (Withers et al., 2021).

### 2.4.2 Helical (Spiral) CT Scanning

The introduction of helical or spiral CT scanning in the early 1980s was a groundbreaking development. Helical CT allowed for continuous volume acquisition as the patient table moved smoothly during the scan. This innovation significantly reduced scan time and enabled the reconstruction of multiple slices in a single rotation. Helical scanning became the standard for most clinical applications (Withers et al., 2021).

## 2.5 Multi-slice CT Scanners

Multi-slice CT scanners are advanced systems equipped with multiple-row detector arrays that allow for the simultaneous acquisition of up to 4 slices, significantly increasing volume coverage and reducing scan times, these scanners utilize new technologies like helical interpolation algorithms and z-filtering reconstruction to enhance image quality and artifact control. Compared to single-slice CT, multi-slice CT offers advantages such as improved temporal and spatial resolution, adjustable slice thickness, and faster acquisition times, leading to potential contrast media savings. They are particularly beneficial for exploring areas like the chest, heart, vessels, musculoskeletal system, and for trauma patients. The development of multi-slice CT represents a significant milestone in radiological practice, promising to revolutionize imaging capabilities similar to the impact of spiral systems in the past (Hsieh and Flohr, 2021).

### 2.5.1 Evolution of Multi-slice CT Scanners

Multi-slice CT scanners have come a long way since their introduction. The evolution of this technology has seen significant improvements in image quality, speed, and clinical utility. Early Multi-slice CT Scanners: The concept of acquiring multiple slices during a single gantry rotation was first introduced in the 1990s. Early multi-slice CT scanners could capture four slices per rotation, allowing for faster imaging than single-slice scanners. 16-Slice CT Scanners: In the early 2000s, 16-slice CT scanners were introduced, further improving image quality and clinical applications. These scanners could provide thin-slice images in a short time, making them ideal for cardiac and vascular imaging. 64-Slice and Beyond: The development of 64-slice CT scanners around the mid-2000s represented a significant leap forward. These scanners offered even faster scan times, higher spatial resolution, and the ability to perform advanced cardiac imaging, such as coronary CT angiography (CTA). Subsequent generations of multi-slice CT scanners continued to increase the number of detector rows, with 128-slice, 256-slice, and 320-slice scanners becoming available. These advancements allowed for improved image quality and expanded clinical applications (Ulzheimer et al., 2019).

## 2.6 Single versus multi-slice CT

The inception of CT imaging in the 1970s marked a significant milestone in medical diagnostics. The earliest CT scanners were single-slice machines that produced one cross-sectional image per rotation (Hounsfield, 1973). These single-slice scanners provided invaluable insights into the human anatomy and disease pathology but had limitations in terms of scan speed, image quality, and clinical applications (Mehta et al., 2023).

The breakthrough came with the development of multi-slice CT scanners, which enabled the simultaneous acquisition of multiple slices during a single rotation. This innovation significantly improved scan speed, allowing for rapid whole-body imaging and reducing motion artifacts. Multi-slice CT scanners quickly gained popularity, transforming the field of radiology and expanding the range of clinical applications (Mehta et al., 2023).

### 2.6.1 Radiation Dose

The issue of radiation dose is a critical consideration in medical imaging, therefore patients are exposed to ionizing radiation during CT scans, and minimizing radiation dose while maintaining diagnostic accuracy is a paramount concern.

Single-slice CT scanners typically expose patients to lower radiation doses compared to their multi-slice counterparts (Brix et al., 2003). This characteristic makes single-slice CT a safer choice, particularly for pediatric and pregnant patients. Lower radiation doses also reduce the risk of long-term radiation-related effects, further emphasizing the importance of single-slice CT in specific clinical scenarios (Joyce et al., 2020). However, it is important to note that advancements in multi-slice CT technology have led to significant improvements in dose reduction techniques. These advancements include iterative reconstruction algorithms, automated exposure control, and tube current modulation (Joyce et al., 2020). These innovations have made multi-slice CT scanners safer by reducing radiation exposure while maintaining image quality, thus narrowing the gap between single-slice and multi-slice scanners in terms of radiation dose (Damilakis, 2021).

### 2.6.2 Image Quality

One of the most notable distinctions between single-slice and multi-slice CT scanners is image quality. Multi-slice scanners generally offer superior image quality due to their ability to acquire thinner slices with reduced motion artifacts. This advantage is particularly crucial in certain clinical scenarios.

Multi-slice CT scanners excel in providing high-resolution images, making them ideal for applications such as cardiac imaging, vascular studies, and advanced neurological imaging (Sun et al., 2011). The ability to capture detailed anatomical structures and visualize dynamic processes, such as blood flow, has revolutionized these fields. In contrast, single-slice CT scanners, while capable of producing diagnostic-quality images, may not match the image quality achieved by multi-slice counterparts, especially in demanding scenarios. However, single-slice CT remains adequate for imaging certain anatomical regions with lower resolution requirements, such as extremities and non-contrast head scans (Withers et al., 2021).

## 2.7 Factors Affecting Dose in CT Scanning

Balancing image quality and radiation dose is a crucial aspect of CT scanning. Higher kVp and mAs values can enhance image quality by reducing image noise, improving contrast, and allowing for thinner slice thickness. However, they also increase patient exposure to ionizing radiation, which is a concern for both diagnostic accuracy and patient safety, see Figure 2.3, which show the control panel of CT scanner (Buzug, 2011).

Figure 2.3 Control panel of CT scanner (Buzug et al, 2011).

### 2.7.1 Kilovoltage Peak (kVp)

The kilovolt peak (kVp) represents the energy level of the photon emitted by the source and subsequently passing through the object (Bontrager and Lampignano, 2013). The kVp values in the majority of CT systems typically fall within the range of 120-140 kV (Stoyanov and Vassileva, 2009). The manipulation of kilovolt peak (kVp) results in alterations in both the number and quality of photons. Consequently, an elevation in kVp leads to an augmentation in radiation dosage while simultaneously reducing image noise (Wildberger, 2010). The selection of tube voltages has not been a significant concern in the field of computed tomography (CT) for many decades. The standard voltage of 120 kV represented the prevailing technological advancement, with voltage being raised to the maximum value of 140 kV only in instances when significant attenuation occurred, such as in patients with obesity. The possibility of reducing kilovolts (kV) was seldom contemplated. Recent investigations have shown that it is feasible to achieve a substantial decrease in dosage for contrast-based examinations, such as CT angiography, as well as for skeletal imaging. According to a study conducted by Kalender et al. (Kalender et al., 2009), it is feasible to achieve a dose reduction of 30 to 50% without compromising picture quality when the tube voltage is decreased from 120 to 80 kV in both standard and slender patients.

### 2.7.2 Milliampere-Seconds (mAs)

mAs refers to the product of tube current (measured in milliamperes, mA) and exposure time (measured in seconds, s). It determines the number of X-ray photons produced per unit time, higher mAs values lead to more photons, which can improve image quality but increase patient radiation dose, the appropriate selection of mAs is crucial to striking a balance between image quality and patient radiation dose (Bontrager and Lampignano, 2013). Clinicians must consider various factors when determining the optimal mAs setting, including clinical indications, patient characteristics, and the diagnostic objectives of the scan. Milliampere-seconds must optimize to reaches the minimum radiation dose received by patients, therefore the Automatic Exposure Control (AEC) and Tube Current Modulation are important to use since can reduce the value of mAs according to patient size (Bontrager and Lampignano, 2013).

### 2.7.3 Pitch Factor

The displacement of the table across a full revolution of the gantry is often known as the table pitch or detector pitch. The table pitch is defined as the displacement of the table in millimeters (mm) during a full rotation of the gantry, divided by the beam collimation, which represents the thickness of each slice in millimeters (mm). Tables that move at higher speeds are sometimes referred to as having larger pitches. The acceleration of table speed has the potential to decrease scanning duration and radiation exposure. However, it is important to note that this enhancement may compromise picture quality if the machine's circuitry is unable to effectively process the acquired data at the same pace as the table's movement (Silverman et al., 2001). Figure 2.4 explain the pitch factor from sprawls website.

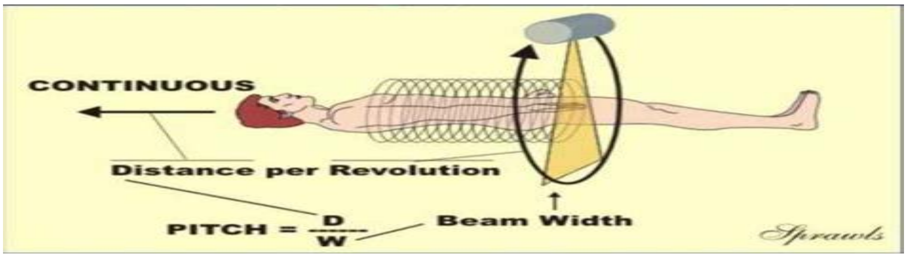

Figure 2.4 Pitch factor from sprawls website.

### 2.7.4 Slice Thickness

The determination of slice thickness values is carried out by the operator in line with the clinical examination criteria. Typically, these values range from 1 to 10 mm (Alshipli and Kabir, 2017). The thickness of the slice has an impact on both the radiation dose and the quality of the image. In order to maintain the integrity of diagnostic images it is preferable to use thinner slices, which necessitates an increase dose due to the need for extra x-ray photons to sustain image quality (Ewaidat, 2013). See Figure 2.5 which explains the slice thickness (Bushberg and Boone, 2011).

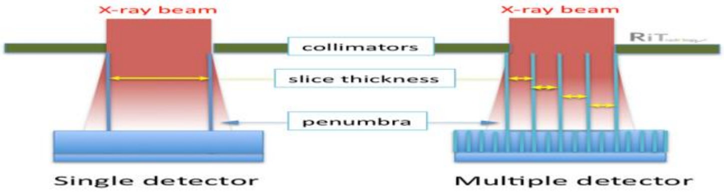

Figure 2.5 Slice thickness explanation (Bushberg and Boone, 2011).

## 2.8 Safety Practices and Guidelines for CT scans

CT delivered high radiation doses compared to other imaging modalities, such as conventional radiography, have raised significant concerns about patient safety (Wasserthal et al., 2023). The need for effective radiation safety practices has become a critical focus in the field of diagnostic imaging to balance the clinical benefits of CT with the potential risks of ionizing radiation exposure.

Ionizing radiation from CT scans can cause biological effects, ranging from deterministic effects at high doses to stochastic effects, such as an increased lifetime risk of cancer at lower doses, these risks are particularly concerning sensitive populations, including pediatric patients and individuals undergoing repeated imaging studies. Studies have demonstrated that CT contributes significantly to the cumulative radiation exposure of the general population, emphasizing the need for optimized imaging protocols and safety measures (Cao et al., 2022).

International organizations, including the International Commission on Radiological Protection (ICRP) and the American College of Radiology (ACR), have developed guidelines to minimize radiation risks associated with CT imaging. These guidelines emphasize the principles of justification, optimization, and dose limitation. Justification ensures that every CT scan is clinically warranted, avoiding unnecessary imaging. Optimization involves tailoring scan parameters, such as tube current, voltage, and pitch, to achieve diagnostic-quality images at the lowest possible dose. Dose limitations establish thresholds for radiation exposure, particularly for vulnerable populations (Marth et al., 2024).

Advances in CT technology have played a pivotal role in improving radiation safety. Innovations such as automatic exposure control (AEC), iterative reconstruction algorithms, and dual-energy CT systems have significantly reduced radiation doses without compromising image quality (Booij et al., 2020). Additionally, dose monitoring software enables real-time tracking of radiation exposure, allowing institutions to adhere to dose reference levels (DRLs) and benchmark their practices against national and international standards (Booij et al., 2020).

In clinical practice, effective communication among radiologists, technologists, and referring physicians is essential to promote radiation safety. Education and training programs have been shown to enhance awareness of radiation risks and the importance of adhering to safety protocols. Moreover, the adoption of standardized imaging protocols and patient-specific dose optimization strategies further ensures consistent application of radiation safety measures (Bárdyová et al., 2021).

Despite significant progress, challenges remain in the widespread implementation of radiation safety practices. Variability in institutional policies, resource constraints, and lack of awareness among healthcare providers can hinder compliance with safety guidelines. Future efforts should focus on integrating radiation safety education into medical curricula, promoting research on dose optimization techniques, and developing robust quality assurance programs (Booij et al., 2020).

## 2.9 Advancements in CT Dosimetry

Throughout the past few decades, the population's exposure to radiation from CT scans has increased. As a result, organizations such as the Food and Drug Administration (FDA), the International Atomic Energy Agency (IAEA), the American College of Radiology (ACR), the National Institutes of Health (NIH), and the Image Gently Alliance have recommended reporting radiation exposure from CT scans. Currently, radiation dose parameters, including the CTDI, DLP, and effective dose, are commonly used to quantify and report radiation exposure (Joseph et al., 2021).

A suitable dose descriptor must be defined in CT dosimetry due to the geometry of the device and radiation. The CTDI, or computed tomography dose index, is regarded as a CT dose descriptor. DLP, which reflects the entire dose in an exhaustive test, is yet another reference quantity (Janbabanezhad Toori et al., 2015). To reflect more precise estimates of patient doses, a new method called "size specific dose estimate" (SSDE) has been put forth in (AAPM) report 204 (Medicine, 2011; Zira et al., 2017).

CT dosimetry is a critical field of study that focuses on quantifying and optimizing the radiation doses delivered during CT scans to ensure patient safety. The history of CT dosimetry dates back to the early days of CT imaging in the 1970s. Initially, dosimetry efforts were primarily concerned with measuring radiation output and estimating patient dose based on technical parameters such as tube current and exposure time. However, the field has evolved significantly, driven by technological advancements in CT scanner design and the increasing awareness of the need for dose optimization (Damilakis, 2021).

According to Damilakis (2021), significant advancements in CT dosimetry have been made, aiming to reduce radiation exposure while maintaining image quality. These advancements include iterative reconstruction algorithms; the introduction of iterative reconstruction algorithms has allowed for dose reduction by improving image quality at lower radiation levels. These algorithms optimize image reconstruction and noise reduction, enabling lower tube currents. Automatic Exposure Control (AEC); is systems adjust tube current based on patient size and anatomy, ensuring that the appropriate amount of radiation is used for each individual, further reducing unnecessary exposure. Photon Counting CT; Emerging technologies like photon counting CT have the potential to revolutionize CT dosimetry. These scanners can provide superior dose efficiency, spectral imaging capabilities, and material decomposition, enabling more accurate diagnosis with lower doses.

Kalender (2014) discusses the critical importance of managing radiation dose levels in computed tomography (CT) imaging, which is a widely used diagnostic modality. The article highlights that while CT is a powerful diagnostic tool, the exposure to ionizing radiation must be closely monitored to ensure patient safety. Also, the article emphasizes the distinction between scanner dosimetry and patient dosimetry. Scanner dosimetry, measured using metrics like CTDIvol (volumetric CT dose index), is well-regulated and enforced for clinical CT scanners. It plays a crucial role in assessing scanner performance and comparing different scan protocols. Patient dosimetry, on the other hand, involves estimating the actual absorbed radiation dose by the patient. This estimation is often based on Monte Carlo (MC) calculations calibrated by CTDI measurements in air and related to anthropomorphic voxel phantoms or patient data. While the dose length product (DLP) is commonly used to estimate effective dose for dose surveillance purposes, accurate estimates of organ