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Estimation and Comparison of Organ-Specific and Effective Radiation Doses in Diagnostic Imaging Procedures

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Abstract: *Exposure to radiation beyond the normal background rate can lead to various severe and long-term health challenges, with the severity depending heavily on the amount of dose received, the dose rate, and individual sensitivity. This study evaluated organ-specific and effective radiation doses among patients undergoing diagnostic imaging at Garkuwa Specialist Hospital, Kaduna, with supporting data from Ahmadu Bello University Teaching Hospital Shika and Barau Dikko Teaching Hospital, Kaduna. Using Thermoluminescent Dosimeters (TLDs) and Monte Carlo-based PCXMC software, effective doses were estimated for eight anatomical regions during fluoroscopy and computed tomography (CT) examinations. Results revealed that fluoroscopy delivered effective doses ranging from 0.25 mSv to 0.60 mSv, whereas CT scans imparted significantly higher doses of 3.00 mSv to 13.60 mSv. The pelvis, thorax, and spine exhibited the highest dose levels due to greater tissue density and thickness. The findings highlight the need for dose optimization, adherence to the ALARA (As Low As Reasonably Achievable) principle, and informed clinical justification when selecting imaging modalities. The study concludes that CT examinations impart up to thirty-two times more radiation than comparable fluoroscopic procedures. It recommends restricting CT use to cases where its superior diagnostic value is indispensable, regularly reviewing imaging protocols, and incorporating patient-specific factors such as age, body mass index, and organ sensitivity into future dose assessments to enhance patient safety and optimize diagnostic quality***.

Keywords—Effective dose, Diagnostic imaging, Fluoroscopy, CT scan, Radiation safety, Monte Carlo simulation

1. INTRODUCTION

Diagnostic X-ray imaging uses ionizing radiation that deposits some energy within the patient's body throughout the examination procedure. It is considered the largest artificial radiation source that causes exposure to the public, and it contributes about 14% of the total annual exposure from all types of radiation sources (Muhogora et al., 2008).

X-rays are a type of electromagnetic radiation with high energy and short wavelengths. They are used in medical imaging to produce images of internal structures, such as bones lungs, and soft tissues. X-rays are produced when high-energy electrons collide with a metal target, such as tungsten. Nonetheless, X-ray examinations have been used extensively in routine and emergency diagnostic imaging because it provides a fast diagnosis for several diseases. Radiological risk assessment from diagnostic X-ray examinations is of great concern where patients might be exposed to doses that could cause deterministic effects. If deterministic effects are avoided by using good imaging practices, the risk of stochastic effects still must be considered (Hart et al., 2002). Hence, in any diagnostic X-ray examination, it is necessary to apply a quality assurance program to ensure that the patient doses maintained as low as is reasonably achievable (ALARA) without affecting image quality(Tapiovara & Siiskonen, 2008).Standard radiographic examinations exhibit a wide variation in dose levels in different countries .These variations have encouraged many countries to establish their own reference dose levels to optimize patient protection and construct their own data base of patient doses, which is best suited for their radiological techniques .Therefore, quantifying the radiological risk to diagnostic radiography patients has been a subject of interest to several organizations and researchers worldwide .Entrance surface air kerma (Kae) has been frequently used to establish a diagnostic reference level for radiographic examinations because it is simple to measure, and it gives an indication of the maximum skin dose; but, the Kae provides little information about the biological health risks associated with the examination(Shamsi et al., 2020).

However, the International Commission on Radiological Protection (ICRP) has introduced the effective dose (E) as the quantity that provides a patient's risk for stochastic effects (cancer and genetic effects) from the radiation exposure (Lahham et al., 2018). Effective dose is a measure of the overall radiation exposure risk to a patient. It's calculated by summing the organ equivalent dose for different organs and tissues, weighted by their sensitivity to radiation induced harm. Effective dose in this context refers to the weight sum of the equivalent doses to organs and tissues in the body from radiological examinations. Effective dose is considered to provide a causal relationship between radiation dose and the occurrence of stochastic effects. This quantity can be used to compare the radiological risk from different radiological examinations with respect to a reference person because it is easy to deal with a single parameter instead of using the values of dose to various organs and tissues. Several mathematical models are used to calculate organ and effective doses due to radiographic examinations; most of them employ the Monte Carlo simulation technique that can be implemented using software programs such as Dose Cal and PCXMC. In this research, organ and effective doses were calculated using the PCXMC software developed by the Finish Centre for Radiation and Nuclear Safety STUK. This software uses computational hermaphrodite phantoms, which mimic patients of different ages and sizes. This method simulates the random interactions of the incident photons, which result in energy deposition to computational phantom organs, and records the deposited energy for each interaction event.

Although several studies have estimated the effective doses for the common diagnostic X-ray examinations in various parts of the world (Begum, 2001). In Saudi Arabia, only two studies were conducted to assess the effective dose for patients associated with CT examinations. Therefore, the lack of this type of study in Saudi Arabia motivated this research. Thus, the present study aims to estimate the organ and effective dose for the patients undergoing a variety of diagnostic X-ray examinations. The results presented in this work will help to establish a reliable database of the dose levels in Saudi Arabia. This data can be used for future comparisons with different X-ray procedures and different hospitals in the country (Osei & Darko, 2013).

Medical diagnostic X-ray procedures are indispensable tools in modern healthcare for the early detection and management of diseases. However, they expose patients to ionizing radiation, which can potentially lead to stochastic effects such as cancer. The challenge lies in quantifying the radiation doses absorbed by individual organs (organ equivalent dose) and assessing the overall risk to the patient (effective dose).

The study on the estimation and comparison of organ-specific and effective radiation doses in diagnostic imaging procedures is highly significant as it promotes patient-centered care by enhancing safety and minimizing unnecessary radiation exposure. It contributes to evidence-based practice by providing valuable quantitative data that supports informed clinical decision-making and optimizes the selection of imaging modalities. Furthermore, the findings serve as a foundation for developing and refining radiation safety standards and guidelines in medical imaging, ensuring adherence to the ALARA (As Low As Reasonably Achievable) principle. Ultimately, the study facilitates continuous quality improvement by identifying areas where diagnostic x-ray procedures and equipment performance can be enhanced to achieve safer and more effective patient outcomes.

Diagnostic x-ray remains one of the most frequently used imaging modalities in modern medicine due to their effectiveness, accessibility, and low cost. However, they are also the largest man-made source of ionizing radiation exposure to the general population.

Although the radiation doses involved in most diagnostic procedures are relatively low, repeated or inappropriate exposures can increase the lifetime risk of radiation-induced effects, particularly in radiosensitive organs.

This study estimated and compared organ-specific and effective radiation doses in diagnostic imaging procedures. The study assessed the potential radiation exposure to patients and evaluated the associated risks while ensuring that the radiation doses delivered are within the safe limits established by regulatory agencies.

The study also evaluated radiation exposure levels, identifying potential areas for dose optimization, and informing strategies to enhance patient safety and radiation protection practices in diagnostic X-ray imaging at three different Nigerian hospitals: Garkuwa Specialist Hospital, Ahmadu Bello University Teaching Hospital (Shika) and Barau Dikko Teaching hospital, (Kaduna).

2. LITERATURE REVIEW

Diagnostic X-ray imaging plays a pivotal role in modern medicine, providing critical information for the diagnosis and management of various medical conditions (Bushberg et al., 2012). Despite its numerous benefits, the use of ionizing radiation in X-ray examinations exposes patients to radiation doses that, if not properly managed, may pose potential health risks. The estimation of organ equivalent and effective doses is essential in evaluating these risks and ensuring that patient exposures remain within safe limits (ICRP, 2007).

Accurate dose assessment helps optimize imaging procedures by balancing diagnostic image quality with patient safety. International guidelines, such as those from the International Commission on Radiological Protection (ICRP), advocate for continuous monitoring and control of radiation doses, promoting practices like the ALARA (As Low As Reasonably Achievable) principle to minimize unnecessary exposure (ICRP, 2007). Dose estimation not only protects patients but also serves as a key parameter in evaluating the performance and safety of diagnostic radiology equipment (Seibert et al., 2014).

This study reviews the fundamental principles of X-ray imaging, the interactions of radiation with human tissue, radiation dose quantities and measurement units, estimation methods, and the associated health risks. Additionally, it summarizes previous research conducted in this field, providing a comprehensive foundation for the current study.

2.1 X-Ray Imaging and Radiation Interaction with Human Tissue

X-ray imaging is a widely utilized diagnostic tool that employs ionizing radiation to visualize internal anatomical structures. X-rays are generated in an X-ray tube when high-velocity electrons collide with a metal target, producing electromagnetic radiation with energies sufficient to penetrate human tissues (Bushberg, et al.,2012). The variations in tissue absorption create contrast in the resultant images, allowing for

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detailed visualization of bones, organs, and other internal structures.

As X-rays traverse the human body, they interact with tissues primarily through photoelectric absorption and Compton scattering. These interactions are fundamental to both image formation and radiation deposition. Other interactions, such as coherent scattering and pair production, occur at much lower frequencies in diagnostic radiology due to the relatively low energy of diagnostic X-rays (Bushong, 2013).

The extent of these interactions depends on factors like photon energy (tube voltage), tissue density, and thickness. Increasing photon energy enhances X-ray penetration but reduces tissue absorption, leading to lower image contrast and decreased patient dose. Conversely, lower photon energies increase tissue absorption, enhance image contrast, but may elevate patient dose (Seibert et al., 2014).

2.2 Organ Specific Dose (D_T) and Effective Dose (E)

Organ-specific dose is the energy absorbed per unit mass of a specific organ or tissue (Osei et al., 2013). It is the most fundamental quantity for assessing deterministic effects and is crucial for organs located directly within the primary radiation beam, where doses can be high (Mettler et al., 2012).

Effective dose (E), expressed in Sieverts (Sv), is a calculated quantity intended to represent the stochastic risk from non-uniform partial-body exposure in terms of an equivalent whole-body exposure (Osei et al., 2013). It is calculated weighted sum of equivalent doses to all specified organs and tissues as indicated in the following equation:

$$E = \sum_T w_T \cdot H_T = \sum_T w_T \cdot D_T . w_R \quad (1)$$

where w_T is the tissue wheighting factor, H_T is the equivalent dose, D_T is the absorbed dose to the organ, and w_R is the radiation weighting factor (which is 1.0 for x-rays) (ICRP, 2007). The values of w_T are defined by the International Commission on Radiological Protection (ICRP), and differences in these factors can lead to variations in the calculated effective dose (Huda et al., 2010).

3. METHODOLGY

Thermoluminescent Dosimeters (TLDs) were used to measure entrance skin doses for patients undergoing fluoroscopy and CT examinations at Garkuwa Specialist Hospital. Additional data were collected from ABU Teaching Hospital, Shika, and Barau Dikko Teaching Hospital. The PCXMC Monte Carlo software was employed to estimate organ equivalent doses and compute effective doses using tissue weighting factors from ICRP Publication 103. Computed Tomography (CT) parameters included tube voltage (kVp), current (mA), rotation time, and pitch, while fluoroscopy parameters included exposure time and beam area.

3.1 Computed Tomography Procedure

Estimation of organ dose from CT procedure requires the user to supply a measured or estimated free-in-air computed tomography dose index (CTDI100, air), tube current (mA), tube rotation time(s), and pitch. The effective dose is calculated as the sum of the weighted equivalent dose in all the tissues and organs of the body as specified in the International Commission on Radiological Protection report 103 (ICRP-103).

Computed tomography (CT) is a diagnostic imaging test used to create detailed images of internal organs, bones, soft tissue and blood vessels. The cross-sectional images generated during a CT scan can be reformatted in multiple planes and can even generate three-dimensional images which can be viewed on a computer monitor, printed on film or transferred to electronic media. CT scanning is often the best method for detecting many different cancers since the images allow your doctor to confirm the presence of a tumor and determine its size and location. CT is fast, painless, non-invasive and accurate. In emergency cases, it can reveal internal injuries and bleeding quickly enough to help save lives. On internal organs that cannot be visualized when subjected to light a contrast reagent is employed for clear diagnosis.

3.2 Fluoroscopy Procedure

Fluoroscopy is a study of moving body structure like an X-ray movie. A continuous X-ray beam is passed through the body part being examined. The beam is transmitted to a TV-like monitor so that the body part and its motion can be seen in detail. Fluoroscopy, as an imaging tool, enables radiologists to look at many body systems, including the skeletal, digestive, urinary, respiratory, and reproductive systems.

4. RESULTS AND DISCUSSION

Table 1, table 2 and figure 1 and 2 show the summary of patient characteristics and the technical parameters used for the various types of examination in this study. The tables show the estimated effective doses from computed Tomography and Fluoroscopy examination for adults, the effective doses were measured for eight (8) anatomical regions, and it was calculated using a device called "THERMOLUMINISCENT DOSIMETER". The highest effective dose for fluoroscopy was observed to be pelvis (AP/L) and spine (AP/L) which are 0.60mSv and 0.58mSv respectively, followed by the moderate doses, AP thorax and AP cervical spine with the value of 0.53mSv and 0.42mSv. Conversely, the lowest effective dose was 0.25mSv for femur. The higher doses in the pelvis and spine regions can be attributed to the increased tissue thickness and bone density in these areas, requiring higher radiation exposure for adequate image quality.

Table 1: Fluoroscopy results

S/N	Organs	Voltage (kV)	Current (mA)	Absorbed Dose (mGy)	Weighting Factor ICRP 106	Effective Dose (mSv)
1	Elbow (L)	55.00	5.00	1.01	0.12	0.30
2	Spine (AP/L)	80.00	14.00	1.20	0.12	0.58
3	Chest (AP)	75.00	2.54	0.35	0.12	0.29
4	Forearm (AP/L)	50.00	3.54	0.48	0.12	0.38
5	Femur (AP/L)	50.00	4.50	1.57	0.12	0.25
6	Thorax (AP)	82.00	14.00	1.11	0.12	0.53
7	Cervicalspine (AP/L)	80.00	3.92	0.60	0.12	0.42
8	Pelvis (AP/L)	70.00	2.81	1.00	0.12	0.60

Table 2: Computed Tomography (CT) Scan Results

S/N	Organs	Voltage (kv)	Current (mA)	Absorbed Dose (mGy)	Weighting Factor ICRP 106	Effective Dose (mSv)
1	Elbow (L)	100.00	145.00	6.55	0.12	4.52
2	Spine (AP/L)	120.00	150.00	12.60	0.12	9.01
3	Chest (AP)	110.00	90.00	8.00	0.12	7.90
4	Forearm (AP/L)	90.00	75.00	7.12	0.12	6.30
5	Femur (AP/L)	100.00	120.00	10.30	0.12	8.00
6	Thorax (AP)	115.00	80.00	14.10	0.12	12.20
7	Cervical spine (AP/L)	70.00	130.00	4.21	0.12	3.00
8	Pelvis (AP/L)	85.00	97.00	14.00	0.12	13.60

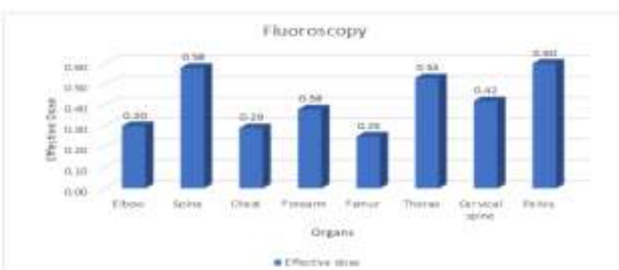

Figure 1: Bar chart showing the organ effective doses for Fluoroscopy

Figure 2: Bar Chart showing the organ effective doses for CT scan.

However, Computed Tomography examination demonstrated significantly higher effective doses, ranging from 3.00mSv to 13.50mSv. The highest effective dose for CT was observed to be pelvis (AP/L), Thorax (AP) and Spine (AP/L) which are 13,60mSv, 12.20mSv and 9.01mSv, followed by the moderate doses, Femur (AP/L), Chest (AP) and Forearm (AP/L) with the values of 8.00mSv, 7.90mSv and 6.30mSv. The lowest effective dose was Elbow (L) and Cervical Spine (AP/L) with the values of 4.52mSv and 3.00mSv.

The differences in effective doses between fluoroscopy and CT highlights the importance of justification and optimization principles in medical imaging. The data demonstrates that CT examinations carry significantly higher radiation burden with doses ranging from 7 to 32 times higher than corresponding fluoroscopic procedures, complex anatomical areas like the pelvis and thorax receiving higher doses. While the risk remains relatively low, they underscore the importance of appropriate clinical justification, especially for CT examinations.

When compared with international diagnostic reference levels (DRLs) recommended by the International Commission on Radiological Protection (ICRP) and the European Commission (typical adult CT effective doses of 5–10 mSv for chest and 10–15 mSv for abdomen/pelvis examinations, and fluoroscopy doses generally below 1 mSv), the effective doses obtained in this study—0.25–0.60 mSv for fluoroscopy and 3.00–13.60 mSv for CT—fall within the acceptable global range. However, the higher CT values observed for pelvic and thoracic regions (up to 13.60 mSv) approach the upper limits of these international benchmarks, underscoring the need for continued dose optimization and adherence to the ALARA principle.

5. Conclusion and Recommendations

This analysis demonstrates the significant variation in effective doses between fluoroscopy and Computed Tomography imaging across different anatomical regions. It is very vital in the diagnostic radiology departments to monitor and control doses to patients during imaging procedures. The doses delivered to patients in any medical imaging procedure should always be optimized for the given purpose. The data emphasizes the continued importance of radiation protection principles in medical imaging practice, ensuring that the benefits of diagnostic imaging outweigh the associated radiation risks. The highest effective dose for fluoroscopy was recorded to be 0.60mSv and 13.60mSv was measured as the highest effective dose for CT, and the lowest effective dose for Fluoroscopy recorded in this research is 0.25mSv and 3.00mSv for CT.

Given the significant dose differences, It is recommended that CT examinations should be reserved for cases where the superior soft tissue contrast and cross-sectional imaging capabilities provide essential diagnostic information not obtainable through fluoroscopy or other lower dose modalities.

Future studies should consider patient specific factors such as age, body mass index and organ sensitivity to provide more personalized dose assessments and risk evaluations.

Regular review of imaging protocols should be conducted to ensure doses are As Low as Reasonably Achievable (ALARA) while maintaining diagnostic quality.

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