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Quantifying Radiation Dose and Risk in Diagnostic X-ray and Computed Tomography Imaging Procedures

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ABSTRACT

This study focused on evaluating the radiation doses received by patients during diagnostic X-ray and CT scan procedures at two healthcare facilities: Abubakar Tafawa Balewa University Teaching Hospital (ATBUTH) and Specialist Hospital, Bauchi. The objective was to quantify radiation exposure and identify factors influencing dose variations, aiming to enhance patient safety and optimize imaging protocols. The study employed thermoluminescent dosimeters (TLDs) to measure radiation doses from procedures on 50 patients: 25 receiving X-ray imaging and 25 receiving CT scans. The study recorded an average effective dose of 0.018 mSv for X-ray procedures and 1.7 mSv for CT scans, demonstrating a significantly higher radiation exposure for CT imaging. We compared the experimental results with theoretical dose estimates from the Davies, Kepler, and Faulkner models. The models overestimated patient doses, with deviations reaching up to 46.2%, highlighting discrepancies between theoretical predictions and measured values. The study identified key factors contributing to dose variations, including photon energy, exposure duration, and source-to-target distance. These findings underscore the complex interplay of technical and procedural variables in determining patient radiation exposure. The results emphasize the importance of routine dose monitoring and the calibration of imaging equipment to minimize unnecessary radiation risks. The findings also advocate for the refinement of theoretical models to better align with real-world clinical practices. Overall, this research reinforces the critical need for balancing radiation safety with diagnostic image quality in medical imaging protocols.

Keywords: Radiation Dose, X-ray, Computed Tomography, Thermoluminescent Dosimeter (TLDs), Dose Optimization

INTRODUCTION

Medical physics plays a critical role in modern healthcare by bridging the gap between physics and medicine to enhance diagnosis and treatment. This multidisciplinary field encompasses various technologies, including diagnostic modalities such as X-ray imaging and computed tomography (CT) scans and therapeutic techniques like radiation therapy and laser treatments (The Association of Medical Physicists and Biomedical Engineers, n.d.). Medical physicists actively transform fundamental scientific discoveries into practical tools that benefit patient care through translational research.

Sophisticated imaging techniques represent one of the most notable advancements in medical physics. Over the past few decades, technologies like CT and magnetic resonance imaging (MRI) have revolutionized diagnostics. These tools enable clinicians to visualize internal structures with sub-millimeter precision. Such advancements have improved early-stage disease detection—particularly for cancer—leading to better treatment outcomes and enhanced patient care (Ahuja et al., 1986).

However, while medical imaging has brought many benefits, it also presents certain risks. Diagnostic tools like X-rays and CT scans rely on ionizing radiation, which, although low, carry the potential risk of inducing cancer with excessive or repeated exposure (National Cancer Institute, 2023). Balancing therapeutic and diagnostic benefits with radiation safety has become a critical focus in modern medical physics.

The Research Gap in Patient Radiation Dose Assessment and Its Significance

Despite the widespread use of X-ray and CT imaging, significant gaps exist in understanding the precise radiation doses patients receive. Traditional dose assessment methods, such as thermoluminescent dosimeters (TLDs), often have limitations, particularly in complex anatomical regions. These limitations lead to inaccuracies in estimating radiation dose, either underestimating or overestimating the absorbed dose. These inaccuracies hinder healthcare providers from optimizing imaging protocols to achieve minimal radiation exposure while maintaining diagnostic quality (Brenner & Hall, 2007).

- **Enhancing imaging protocols** by identifying dose-limiting factors and balancing safety with diagnostic quality.
- **Reducing radiation risks** through evidence-based dose management strategies tailored to specific imaging scenarios.
- **Promoting patient safety** by ensuring compliance with international safety guidelines and protocols, reducing cumulative radiation exposure for vulnerable populations, such as children and cancer patients undergoing multiple scans.

By addressing these gaps, healthcare systems can establish safer imaging environments that protect patients and support more efficient medical decision-making.

The lack of standardized dosimetry protocols across healthcare institutions exacerbates these challenges. The inconsistent ways radiation doses are measured, reported, and interpreted hinder effective radiation safety practices. Imaging techniques, equipment calibration, exposure parameters, and patient anatomy further complicate radiation dose quantification and management. These factors create barriers to consistent, reliable dose assessment across different healthcare settings, making it difficult to compare radiation exposure levels and optimize safety practices.

Addressing this research gap holds significant value. Without precise and standardized methods for dose assessment, healthcare providers may inadvertently expose patients to unnecessary radiation, especially during routine imaging procedures. Accurate dose quantification is essential for:

Recent Advancements in Radiation Safety Protocols

Recent innovations have significantly advanced radiation safety protocols to address the risks associated with medical imaging. These advancements include:

1. **Automated Dose Monitoring Systems** Modern imaging equipment now incorporates built-in dose tracking and monitoring systems, such as *DoseWatch* and *Radimetrics*. These systems allow clinicians to track and manage patient exposure during imaging procedures, ensuring compliance with safety standards, and improving consistency.
2. **Patient-Specific Dose Optimization** Advanced software algorithms now enable

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clinicians to adjust radiation doses based on patient size, weight, and anatomical complexity. This approach minimizes unnecessary exposure while maintaining high quality imaging results. Technologies like **Automatic Exposure Control (AEC)** have become standard in CT imaging, optimizing radiation dose in real-time.

3. **Low-Dose Imaging Technologies** Innovations such as low-dose CT protocols, iterative reconstruction algorithms (e.g., ASIR and MBIR), and advancements in detector sensitivity have reduced radiation exposure while preserving image quality. Iterative reconstruction techniques, for instance, reduce image noise and enhance clarity at significantly lower doses compared to traditional methods.
4. **Adoption of International Guidelines** Protocols such as the *ALARA* (As Low As Reasonably Achievable) principle and the *Image Gently* and *Image Wisely* campaigns actively promote dose optimization practices globally. These initiatives prioritize minimizing radiation exposure, particularly for pediatric and high-risk populations, while maintaining diagnostic efficacy.
5. **Radiation Dose Reference Levels (DRLs)** International bodies such as the International Commission on Radiological Protection (ICRP) and other regulatory agencies have established diagnostic reference levels for common imaging procedures. DRLs provide benchmarks for healthcare providers to assess their practices against national or regional standards, encouraging dose optimization and safety.

These advancements enable healthcare institutions to implement safer, more effective imaging practices that prioritize patient safety while maintaining diagnostic precision.

The Need for Accurate Dose Quantification

Given the rapid advancements in imaging technology and safety protocols, clinicians must accurately quantify patient radiation doses from X-ray and CT scans. This study aims to bridge the existing gap by developing robust methodologies to assess radiation exposure during these procedures.

Significance of This Study

The outcomes of this study will significantly improve patient care by:

- **Optimizing imaging protocols** to minimize radiation exposure without compromising diagnostic quality.
- **Supporting the development of dose reduction strategies** tailored to specific imaging technologies and patient populations.
- **Promoting evidence-based guidelines** that ensure patient safety and enhance compliance with international safety standards.

MATERIALS AND METHODS

Study Area

Abubakar Tafawa Balewa University Teaching Hospital (ATBU TH), Bauchi Abubakar Tafawa Balewa University Teaching Hospital (ATBU TH) is a tertiary healthcare institution in Bauchi State, Nigeria. It serves as a teaching hospital for the Abubakar Tafawa Balewa University College of Medicine and Health Sciences. The hospital provides a wide range of medical services, including diagnostic imaging, such as X-ray and CT scans, making it a suitable site for assessing patient radiation exposure.

Specialist-Hospital,Bauchi
Specialist Hospital, Bauchi, offers advanced medical care to patients from Bauchi State

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and surrounding regions. The hospital specializes in radiology and imaging services, including conventional X-ray and CT scans, and plays an important role in the healthcare infrastructure of the area.

Equipment

Thermo Luminescent Dosimeter (TLD) System

LiF (Lithium Fluoride) phosphor badges

Model 4500 TLD reader with Win rems software

X-ray-Machines

Conventional X-ray machines used in various hospitals

CT-Scan-Machine

A computed tomography machine used for imaging procedures

Thermo Luminescent Dosimeter (TLD) Badge Preparation

The thirty thermoluminescent dosimeter (TLD) badges, each containing two lithium fluoride (LiF) detectors, from the Center for Energy Research and Training (CERT), Zaria. We labeled each badge with Arabic numerals to facilitate identification and tracking throughout the study. Prior to use, we annealed the badges to eliminate any residual radiation signal, ensuring the accuracy of the measurements.

Patient Consent and Ethical Approval

The ethical approval from the Ethics Review Committee at both Abubakar Tafawa Balewa University Teaching Hospital (ATBU TH) and Specialist Hospital, Bauchi. The committees reviewed the study's method to ensure it adhered to national and international standards for human subject's research. We get written informed consent from all participants, detailing the objectives of the study, the procedures involved, and the role of TLD badges in measuring radiation exposure during imaging procedures. Participants are aware of their voluntary participation and the confidentiality of their medical information.

Patient Exposure and Data Collection

ATBU TH Radiology Department

We used ten TLD badges to measure patient radiation exposure during conventional X-ray examinations. For each examination, we placed a badge in a dark polythene bag and attached it to the patient's skin near the irradiated tissue. This placement ensured minimal interference with the imaging procedure. After the examination, we carefully removed the badge and stored it in the bag to avoid accidental exposure to external radiation before processing.

Specialist Hospital Bauchi

We employed seventeen TLD badges to measure patient radiation exposure during various imaging procedures. We used two badges for conventional X-ray examinations, following the same procedure as at ATBU TH. For CT scans, we used seven badges. We attached each badge to a strip and placed it on the patient's skin near the region of interest. After each imaging procedure, we removed the exposed badges carefully and stored them in a shielded container to prevent contamination from background radiation.

Post-Exposure Procedures

After the imaging procedures, we collected the exposed TLD badges and transported them to the Centre for Energy Research and Training (CERT), Zaria. At CERT, we processed the TLD badges using a TLD reader, which measured the radiation absorbed by the LiF detectors. We recorded the dosimetric quantities in micro Sieverts (μSv) for each patient. We measured the following dosimetric quantities:

- **Skin Dose**: The radiation dose absorbed by the superficial layers of the skin.
- **Depth Dose**: The radiation dose absorbed at a specified depth within the tissue.
- **Average Entrance Skin Dose (ESD)**: The average radiation dose absorbed by the skin at the point of entry of the X-ray beam.

Uncertainties in Dose Measurement

To minimize and address uncertainties in radiation dose measurements, we implemented several strategies:

1. **Calibration of Equipment** we calibrated the TLD reader before the study to ensure accurate measurement of radiation exposure. We used known radiation sources to calibrate the reader and verify its accuracy and reliability.
2. **Control Badges** we used control badges to account for background radiation and potential contamination. We positioned these badges in areas unaffected by the imaging procedures' radiation and then processed them with the exposed badges to distinguish patient exposure from background radiation.
3. **Standardized Badge Placement** we standardized the placement of the TLD badges to minimize variability in the measurements. We carefully positioned each badge on the patient's skin near the irradiated region to reflect accurately the radiation dose delivered during the imaging procedure.
4. **Repetition of Measurements** we used multiple badges for different imaging procedures, enabling cross-validation of the results. By measuring radiation exposure with several badges placed in original positions, we ensured consistency in the readings and minimized the potential for localized measurement errors.
5. **Data Analysis and Error Estimation** During data analysis, we applied statistical methods to estimate the uncertainty in dose measurements. We calculated standard deviations and conducted sensitivity analyzes to account for variations in patient characteristics (such as body mass and anatomical positioning) that could influence radiation exposure.

RESULT AND DISCUSSION

We categorized the project results into two groups: experimental results from hospitals and theoretical results derived from models. We compared the experimental results with the theoretical findings and relevant published literature.

Since manipulating patients during medical imaging posed risks, we avoided it. Limited time and resources prevented us from obtaining phantoms that could serve as substitutes. We selected the Fitzgerald et al. formula to investigate how various imaging parameters affect the absorbed dose in patients.

The lack of necessary facilities restricted us from conducting experimental work on radiotherapy. However, we estimated the surviving fraction for a standard fractionation radiotherapy schedule using O'Rouke's method to be 7.3×10−77.3 \times 10^{-7}7.3×10−7, Showing a very low probability of repopulation of clonogenic cells with this schedule.

Experimental Results

The results from exposing patients to conventional X-ray and computed tomography machines, as presented in Tables 1 and 2. The average effective doses per exposure measured were 0.018 mSv for plain X-ray and 1.7 mSv for the computed

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tomography machine. We also recorded a background radiation dose of 0.2005 mSv from unexposed TLDs.

Table 1: Effective Dose of patients exposed to conventional X-ray machine

Organ	Entrance skin dose (mSv)	Effective Dose (mSv)
Foot AP	1.8640	0.0186
Elbow	2.0335	0.0203
Lonbascra Spine PA	1.6790	0.0168
Chest AP	1.3785	0.0138
Forearm AP	1.8195	0.0182
Ankle AP	1.8385	0.0184
Shoulder AP	1.5652	0.0157
Chest AP	1.5140	0.0151
Skull (AP/PA)	2.2595	0.0226
Nasal space (AP/PA)	2.0160	0.0202
Skull PA	1.3080	0.0131
Forearm (AP/PA)	2.3160	0.0232

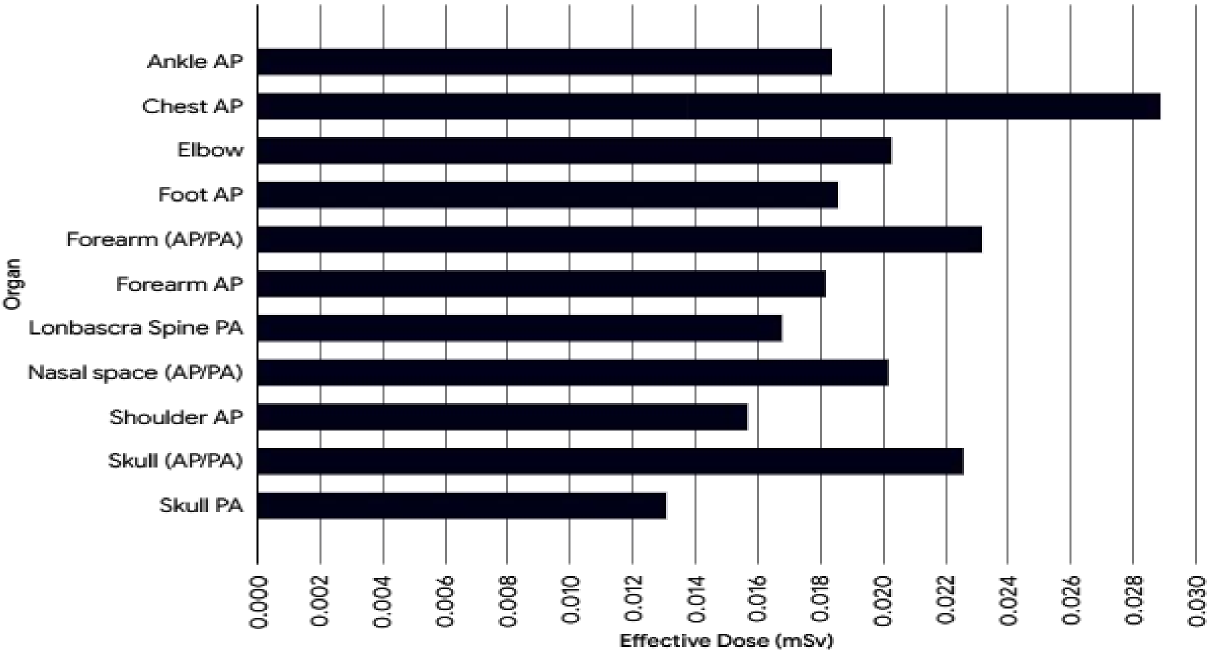

Figure 1: Effective dose of patients exposed to conventional xray machine

Table 2: Effective Dose of patients exposed to Computed Tomography Machine

Organ	Entrance Skin (mSv)	Effective Dose (mSv)
Skull	44.160	2.208
Abdomen	28.745	1.437
Skull	27.775	1.389
Abdomen	30.615	1.531
Abdomen	29.647	1.482
Skull	42.016	2.101

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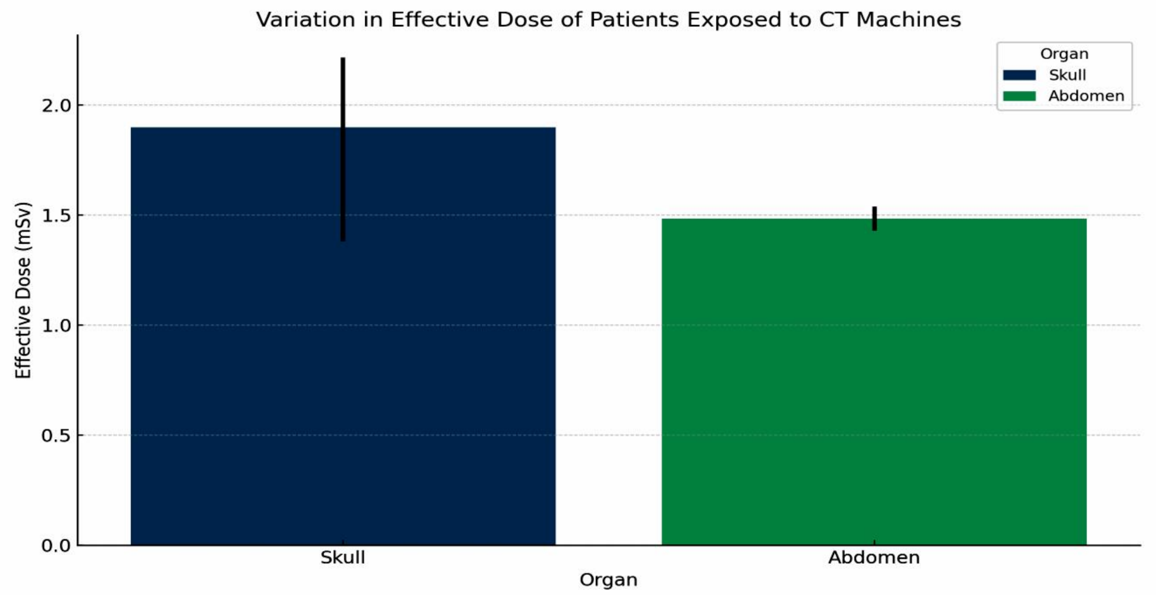

Figure 2: Effective dose of patients exposed to computed tomography machine

We exposed twelve patients of different age groups to a conventional X-ray machine. The exposures targeted different body parts, with quality factors adjusted based on the patient's age and the specific body part. Figure 1 presents these details.

Specifically, we exposed three pediatric patients aged 1-10 years and nine adults aged 10-70 years. Among the adults, four were between 10-30 years old, three were between 30-50 years old, and two were between 50-70 years old. The average effective dose per exposure across all patients was 0.018 mSv.

Figure 2 shows the age range of the patients exposed to the conventional X-ray machine. We used a constant tube voltage of 130 kV for all patients exposed to the computed tomography machine.

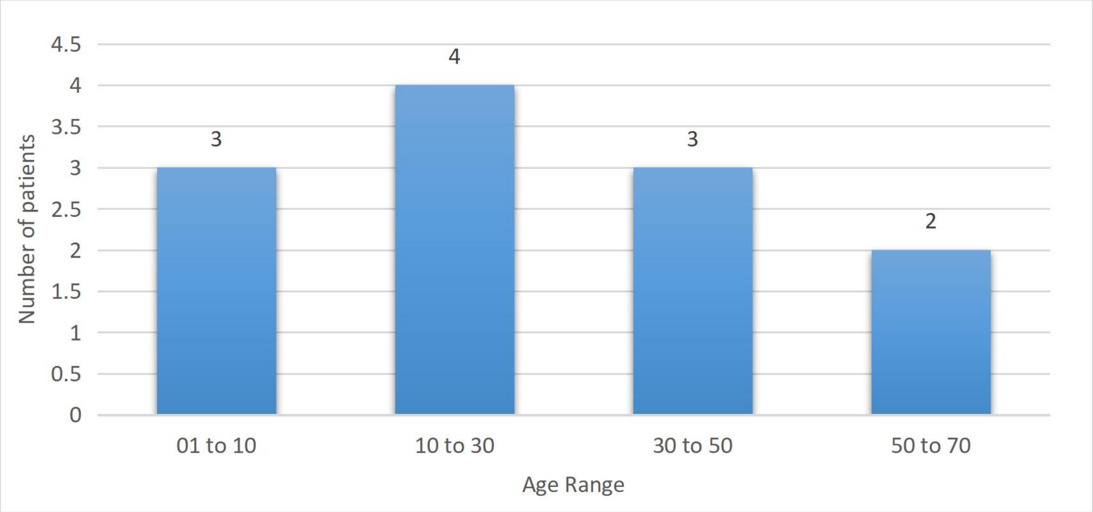

Figure 3: Age Range of Patients Exposed to Conventional X-ray Machine.

Comparison of Result

The mean effective dose of patients exposed to a conventional X-ray machine, as estimated from the entrance skin dose calculated by the Davies, Kepler, and Faulkner models, is 0.039 mSv, 0.0024 mSv, and 0.02 mSv, respectively. These values represent a 46.2%, 13.3%, and 11.1% variation compared to the mean effective dose estimated from the measured entrance skin dose generated experimentally.

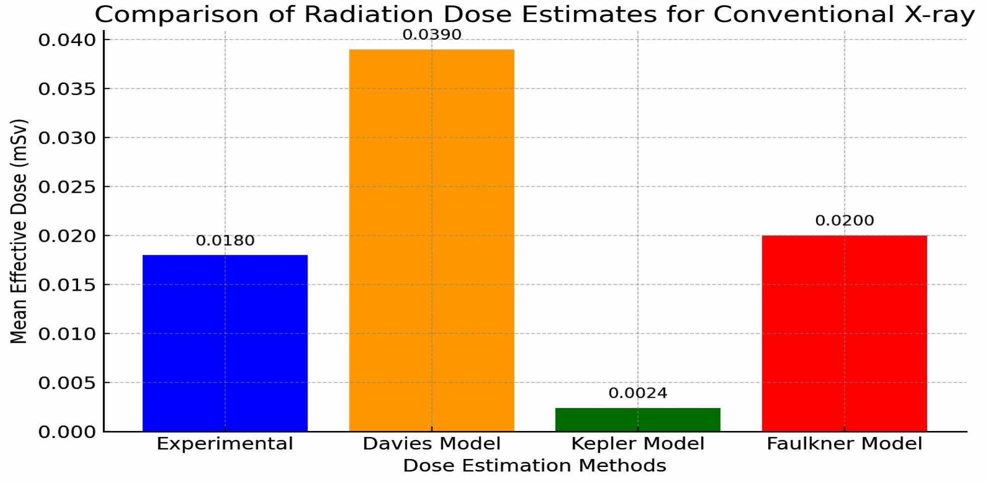

Figure 4: Comparison of radiation dose estimated for conventional X-ray.

Table 3: Comparison of the estimated conventional X-ray machine effective dose value of present study to some published values.

AUTHOR	EFFCTIVE DOSE (mSv)
United Nations (2000)	0.06
Wall BF, Hart D. (1997)	0.01
Present study	0.02

The present study's value (0.02 mSv) aligns closely with Wall BF and Hart D. (1997) (0.01 mSv) but is significantly lower than the United Nations (2000) report (0.06 mSv). As Shown in fig. 4, this variation could reflect differences in imaging protocols, equipment calibration, and patient demographics.

Table 4: Comparison of the estimated Computed Tomography Effective Dose of the present study by some published values.

Procedure	Avg. Effective Dose	Range reported in Literature
CT Head	2.00	0.90 - 4.00
CT Abdomen	8.00	3.50 – 25.00
PRESENT STUDY		
CT Head	1.90	
CT Abdomen	1.00	

The present study's values (1.9 mSv for the head and 1.0 mSv for the abdomen) are lower than the average literature-reported ranges (2.45 mSv for the head and 14.25 mSv for the abdomen).

The average effective dose is more than the range of the recommended average glandular dose by the International atomic Energy Agency, which is 1mSv–3mSv. (IAEA 1995).

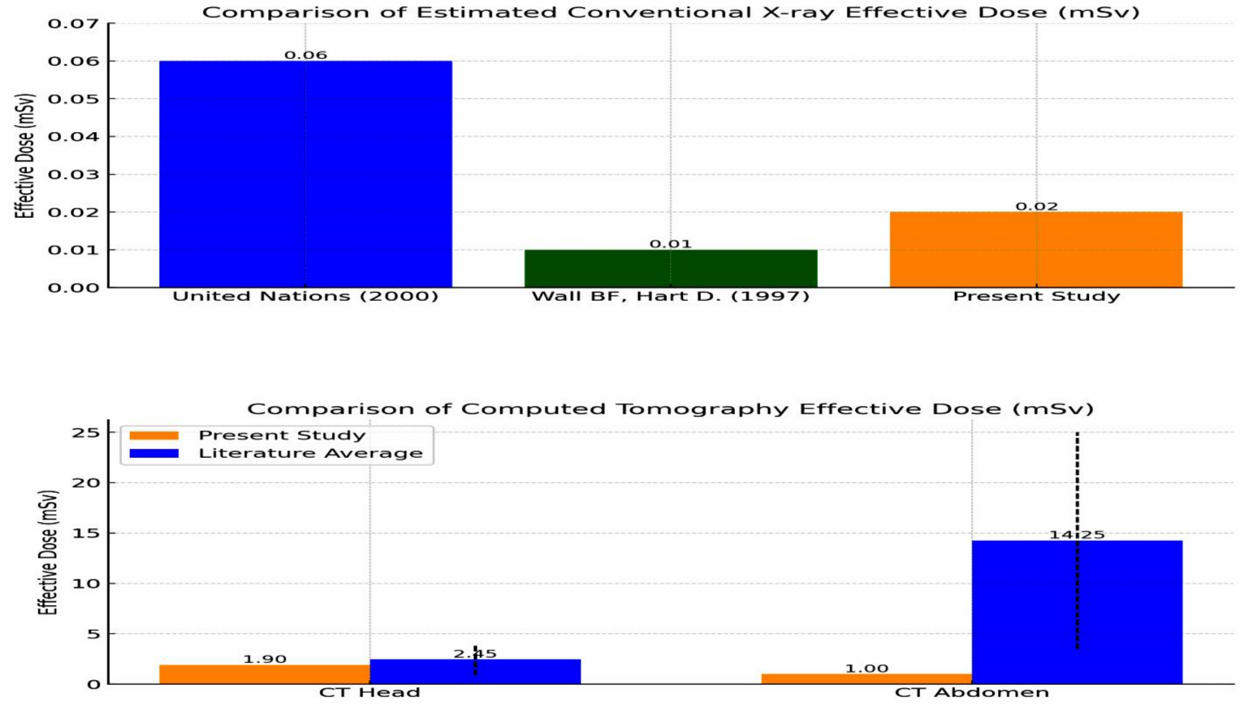

Figure 5: Comparison of ct- scan and xray machine effective dose.

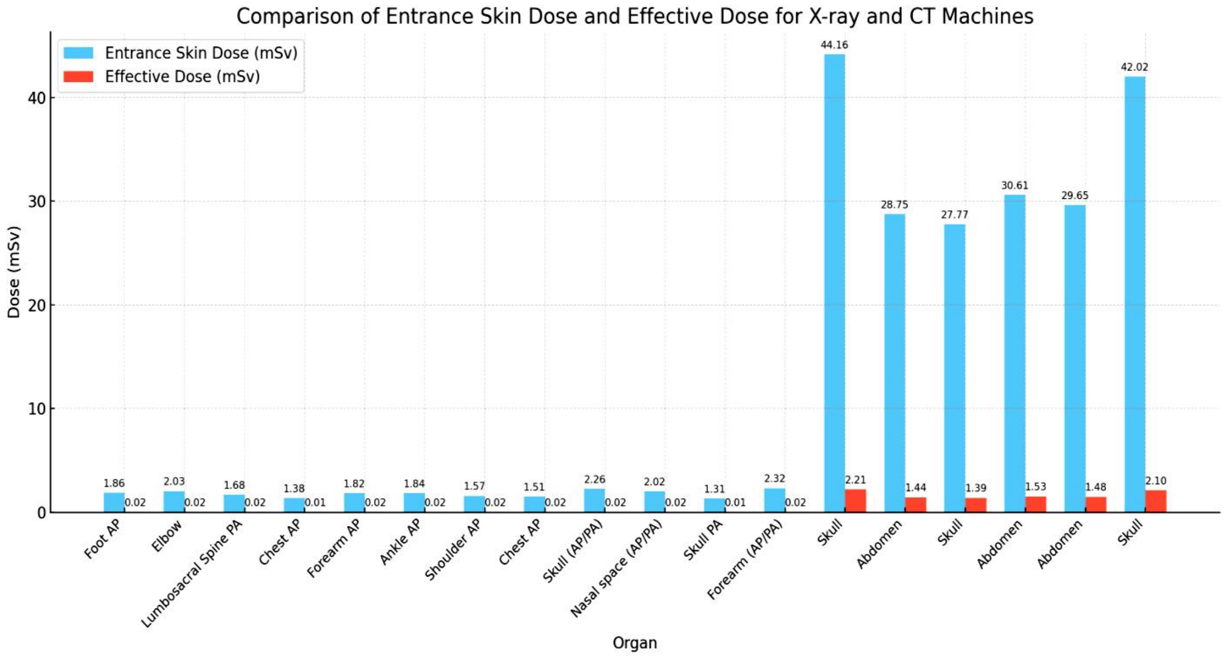

Figure 6: Chart summarizing entrance skin dose and effective dose for both ct and X-ray

A combined bar chart summarizing the Entrance Skin Dose and Effective Dose for both X-ray and CT machines across various organs. The chart highlights variations in dose measurements, offering a comparative view of the two modalities.

Results of Radiobiological Parameters

Table 4: Photon flux of organs exposed to conventional X-ray machine.

Photon Flux φ (photons/cm^2)	**Area A(cm^2)**	**Organ**
1.04 X 10^{16}	12	Foot
1.25 X 10^{16}	10	Elbow
2.60 X 10^{14}	480	Lumbosacral spine
4.0 X 10^{14}	312	Chest
5.34 X 10	234	Forearm
3.13 X 10^{15}	40	Ankle
1.25 X 10	100	Shoulder
1.27 X 10^{14}	988	Skull

The table above shows that as the target area increases, the number of photons per unit area of the target decreases. This reduction in photon density leads to fewer photons being absorbed per unit area of the target, consequently lowering the photon flux.

DISCUSSION

Implications of Findings for Patient Safety and Protocol Optimization

The findings of this study have several critical implications for improving patient safety and optimizing imaging protocols.

Patient Safety

The variation in dose estimates underscores the importance of accurate dose measurement for diagnostic imaging. For instance, the Davies model overestimated effective doses compared to experimental results, while the Kepler model underestimated them. Overestimation may lead to unnecessary restrictions on diagnostic procedures, limiting access to vital imaging for patients. Conversely, underestimation poses significant risks of excessive radiation exposure, potentially resulting in harmful biological effects.

Identifying accurate dose estimates ensures adherence to the "As Low As Reasonably Achievable" (ALARA) principle, a key standard in radiation protection practices.

Protocol Optimization

The study findings highlight the value of experimental dose measurements as benchmarks for refining imaging protocols. Comparing theoretical models to actual patient measurements enables healthcare providers to select and adopt protocols that minimize radiation exposure without compromising diagnostic efficacy.

For example, the mean effective dose for conventional X-ray imaging was experimentally determined as 0.018 mSv, compared to model-based values of 0.039 mSv (Davies), 0.0024 mSv (Kepler), and 0.02 mSv (Faulkner). These variations reinforce the need for equipment calibration and optimization of imaging techniques to align with validated dose ranges.

Understanding dose-related factors—such as exposure time, source-to-target distance, and photon energy—provides a foundation for developing patient-specific imaging protocols.

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Study Limitations

One significant limitation of this study was the inability to use phantoms for dose measurement and imaging simulations. Phantoms are essential in radiology research because they mimic human tissue properties, allowing for controlled experimentation without exposing patients to additional risks.

Impact of Not Using Phantoms

Ethical and logistical constraints limited the ability to manipulate patient positioning, exposure times, and other imaging parameters. This restriction may have affected the comprehensiveness of the study in evaluating dose variations across different imaging conditions.

The reliance on direct patient measurements introduces variability, as factors such as body habitus, age, and individual anatomy could influence dose absorption.

Summary

The study successfully quantified patient radiation doses during diagnostic imaging and highlighted dose variations between experimental measurements and theoretical predictions. While experimental results provided critical insights, the lack of phantoms constrained the scope of analysis. These findings emphasize the need for robust dose monitoring systems, regular equipment quality checks, and the integration of phantoms in future research to advance patient safety and protocol optimization in diagnostic radiology.

CONCLUSION

This study assessed radiation doses received by patients during diagnostic imaging using conventional X-ray and Computed Tomography (CT) machines. We compared experimental measurements and theoretical models to understand dose variations and highlight opportunities for improvement in clinical practices.

The results revealed significant variations in radiation doses estimated by theoretical models compared to experimental measurements. For conventional X-rays, the mean effective dose was determined to be 0.018 mSv, while CT scans yielded an average effective dose of 1.7 mSv. We observed variations of 46.2%, 13.3%, and 11.1% when comparing the theoretical estimates from the Davies, Kepler, and Faulkner models against experimental data.

Key dose-related factors included exposure time, source-to-target distance, photon energy, and organ size. Despite constraints such as the inability to use phantoms, the study highlighted critical insights into optimizing radiation exposure and improving safety protocols in diagnostic imaging.

Recommendations

To minimize patient radiation exposure while maintaining diagnostic quality, the following actionable recommendations are proposed.

Protocol Optimization

Develop patient-specific imaging protocols based on experimental dose measurements to minimize unnecessary exposure. Standardize exposure parameters, such as exposure time, photon energy, and source-to-target distance to achieve consistent and optimized dose levels.

Equipment Calibration and Maintenance

Regularly calibrate imaging equipment to ensure accurate radiation output and reduce variations in dose delivery. Conduct periodic quality assurance checks to identify and address potential equipment malfunctions or inconsistencies.

Use of Advanced Dose-Reduction Technologies

Implement dose-reduction tools, such as automatic exposure control (AEC) systems and iterative reconstruction techniques in CT imaging. Adopt digital radiography systems for conventional X-rays, which require lower radiation doses than traditional systems.

Phantom-Based Research

Incorporate the use of tissue-equivalent phantoms in future studies to allow controlled experimentation and accurate dose estimation under various imaging conditions.

Training and Awareness

Train radiologists and technologists on dose optimization strategies, including the application of the ALARA (As Low As Reasonably Achievable) principle. Promote awareness among healthcare providers regarding the implications of dose variations and the importance of adhering to standardized protocols.

Patient Safety Measures

Use shielding devices (e.g., lead aprons) to protect non-targeted areas during imaging procedures. Maintain detailed dose records for patients undergoing multiple imaging procedures to track cumulative exposure and avoid excessive radiation.

Policy and Regulation

Enforce stricter guidelines and regulations for radiation dose limits in diagnostic imaging. Require healthcare facilities to adopt and routinely audit radiation safety protocols**.**

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