Measurement of Patient Radiation Doses during Certain Diagnostic Radiography Procedures

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Author’s contribution

The sole author designed, analyzed and interpreted and prepared the manuscript.

ABSTRACT

Aims: The aims of this study were to measure the radiation dose to patients in certain routine x-ray examinations and to estimate organs equivalent and effective doses.

Study Design: This prospective study included 220 adult patients who underwent 9 radiographic X ray imaging procedures.

Place and Duration of Study: This study was conducted Sharg Elneel Model Hospital (A), Fidail Hospital (B), Al-Amal Hospital (C) and Medical Corps Hospital (D), Khartoum state, Sudan, between June, 2013-August, 2015.

Methodology: The entrance surface air kerma (ESAK) was measured for four radiographic examinations using thermo luminescence dosimeters (TLD-GR200A). A total of 220 patients were examined in four hospitals.

Results: The mean ESAK (mGy) for the chest, hand, knee joint, leg, shoulder, foot, arm, ankle and lumbar spine were 0.40±0.04, 0.36±0.03, 0.64±0.07, 0.39±0.04, 0.35±0.02, 0.54±0.02, 0.26±0.02, 0.46±0.03 and 1.98±1.1, respectively. The overall effective dose was 0.16±0.05 mSv.

Conclusions: The results of ESAK were comparable with previous studies. Patient’s doses showed wide variations in the same types of x-ray examination due to the choice of exposure

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factors, technique, focus-to-film distance, filter, film-screen speed and the output of the x-ray units and processor quality were used.

Keywords: Patient dosimetry; radiography; effective dose; X ray imaging.

1. INTRODUCTION

Medical exposures from radiological procedure constitute 50% of the overall radiation dose compared with 15% three decades ago [1]. Diagnostic imaging constitute up to 78% of medical radiological exposure [2,3]. The advancement in radiographic image acquisition, processing and quality allow the operator to overexpose the patient without having to repeat the radiographs [4]. Since its introduction in 1980s, computed radiography (CR) has increasingly replaced film-screen radiography (FSR) systems due to its numerous advantages [4]. It has been estimated that about 30% to 50% of the important medical assessment is based on radiological examinations [5]. The benefits of properly performed radiological procedures almost always outweigh the radiation risk, if radiological protection principles are applied. These principles include proper justification of the medical procedure and optimization of the practice by using the lowest dose to carry out the procedure without impairing the diagnostic findings, because there are no dose limits for patients undergoing diagnostic imaging procedures [3]. The cancer and the genetic effect probability due to radiation exposure are 5.5% Sv\(^{-1}\) 0.2% Sv\(^{-1}\), respectively, based on the linear no-threshold model (LNT) of radiation induced cancer [3]. Previous studies have confirmed that patients’ doses in diagnostic radiology procedures are below the tissue reaction levels, but hereditary and cancer effects cannot be neglected [3,6-21]. However, the most important radiation protection problem in the diagnostic imaging is the unnecessary exposure which produces an avoidable risk. The unnecessary use of medical radiological examination has been estimated to be in the range of 10%-50% [22,23]. Therefore, patient protection from unnecessary exposure to ionizing radiation is recommended [3]. Patient radiation dose screening is an essential part of quality assurance in medical imaging to ensure obtaining high quality diagnostic images with the least possible radiation dose to the patient. Entrance surface air kerma (ESAK) which is one of the basic dosimetric quantities of patient dose measurement is useful in the evaluation of patient radiation protection measures and for inter-comparison of setting the dose reference level (DRL) at national and international levels [3]. Although, the concern about cancer risks associated with medical radiation has increased in recent years [1,6-24], still few studies have been performed in this field compared to the frequency and radiation risks of the procedures in Sudan. These studies have shown that there is a wide range of ESAK dose values for the same procedure. In addition to that, continuous improvement in image receptors (detectors technology), requires periodic dose assessment [17]. In Sudan, although the number of radiological medical procedures is increasing considerably, still few studies were reported regarding patient safety and protection [14,15,16,20-24]. In addition to that, monitoring is of particular importance because some of the X ray machines are relatively old, without dosimetric performance parameters such as kerma area product meters (KAP) [25,26]. Therefore, it is important to evaluate the patient’s safety and protection in radiology departments. The objectives of this study are to evaluate the performance of x-ray machine and patient doses during diagnostic radiography procedures.

2. MATERIALS AND METHODS

2.1 Patient Samples

A total of 220 patients were examined in four hospitals in Khartoum state: Sharg Elneel Model Hospital (A), Fidail Hospital (B), Alamal Hospital (C) and Medical Corps Hospital (D). The Ethics and Research Committee approved the study and a written consent was obtained from all patients prior to the procedure. The data were collected using a sheet for all patients in order to maintain consistency of the information. The following patient demographic data (age, weight, height, body mass index (BMI) derived from weight (kg) / (height (m))\(^2\) and exposure parameters (tube potential (kVp), tube current time product (mAs)) were recorded. The dose was measured for two main examinations: Chest and lumbar spine and few others examinations (upper and lower limbs and skull X rays). There is no advance preparation necessary for routine x rays. All examinations
were performed according to the technique used in each hospital.

2.2 X-ray Machines

In the present study, three different modalities X-ray machines, from different manufacture were used as described in Table 1.

2.3 Imaging Technique

Projection radiography examinations consist of two views, the frontal view (Antero posterior (AP)) and the lateral (LAT) view. For chest X rays postero-anterior (PA) view is obtained according to the department’s protocol. No additional views are considered in this study. There is no advance preparation necessary for routine radiographic imaging. A cotton gown is used to replace all clothing on the upper body and all metallic objects such as jewelry must be removed from the examined organ. Before the examination, the radiographer explained the procedure to all patients. All examinations were performed according to the technique used in each hospital.

2.4 Patient Dose Measurement

Patient ESAK was measured by attaching an envelope containing 3 TLDs to the patients’ skin on the central axis of the X-ray beam entrance. A batch of 50 circular TLD-GR200A (LiF: Mg, Cu, P) chips of dimension 0.8 mm thickness by 4.5 mm diameter were used for patient dose measurements. GR200A has many characteristics that made it the preferable for patient dose measurements: effective atomic number \(Z_{\text{eff}} = 8.2\) that makes it tissue equivalent \(Z_{\text{eff}}, \text{tissue} = 7.42\), and wide range of linearity (from 10-7 Gy up to 10 Gy). The TLDs were calibrated according to the protocols for the range of energies described previously [27].

The TLD signal was read using an automatic TLD reader (Fimel PCL3, France) in an atmosphere of inert nitrogen. The stability of the reader was checked before any reading session.

The patient dose (D (Gy)) was calculated using equation 1.

\[
D(\text{Gy}) = \left( \frac{\text{TL}_n}{\text{TL}_s} \right) D_s
\]

Where

\(\text{TL}_n\) is the net reading of TLD chip, \(\text{TL}_s\) is the net reading of TL signal which irradiated to a known dose (Ds).

2.5 Quality Control of the X-ray Equipment

Safety requirements for the design of X-ray systems and auxiliary equipment, shielding of facilities, and relevant international safety standards were evaluated in all departments. QC measurements were carried out according to international guidelines [28,29] to evaluate the performance of the X-ray generator and x-ray tube. Visual and environmental inspection and performance testing was also performed.

The following quality control tests were performed (i) kVp accuracy (ii) kVp reproducibility and (iii) Beam alignment & perpendicularity.

2.5.1 Tube voltage accuracy

The multifunction meter was placed on the x-ray table top with source to surface distance (SSD) of 75 cm. Six successive exposures were made using a tube voltage of (50 -80) kVp and 10 mAs. The multifunction meter was cleared after each exposure, then the kVp error (kVp–kVp measure) was measured, the accepted value is \(\pm 5\%\).

2.5.2 Tube voltage reproducibility

The multifunction meter (RMI 240) was placed on the x-ray table top and used for three different kVp were used and data collected for each unit. The multifunction meter was cleared after each exposure, then the kVp error (kVp–kVp measure) was measured, the accepted value is \(\pm 5\%\).

\[
\Delta kVp = \frac{kVp – kVp \text{ measure}}{kVp \text{ measure}} 
\]

Table 1. Type and main characteristics of X-ray machine

| Hospital | Manufacturer | Total filtration (mm Al) | Manufacturing date | Installation year | Image receptor |
|----------|--------------|-------------------------|--------------------|-------------------|---------------|
| A        | Toshiba      | 3.0                     | 2003               | 2009              | SFR           |
| B        | Shimadzu     | 3.5                     | 2007               | 2008              | CR            |
| C        | Toshiba      | 3.0                     | 2011               | 2012              | CR            |
| D        | Toshiba      | 3.5                     | 2004               | 2009              | CR            |
2.5.3 Beam alignment & perpendicularity

The X-ray image acquisition was done on the 18 cm X 24 cm cassette. The test was performed using 60 kVp, 20 mAs and source-skin -distance (SSD) 100 cm. If the X-ray field falls just within the image of the rectangular frame, there is a good alignment. The upper tolerable limit of misalignment is 2% of the SSD in either the width or the length of the x-ray film. The X-ray beam should be perpendicular to the plane of the image receptor for X-ray beam alignment. Acceptable alignment is 1.5°.

3. RESULTS

In this study a total of 220 patients were exposed to conventional X-ray to diagnose different organs in different hospitals in Khartoum state. The results of tube voltage (kVp), timer accuracy, exposure reproducibility, mA and exposure time linearity and radiation output are presented in Table 2. Tube voltage (kVp) accuracy for all hospitals was within acceptable limits. Table 3 presents light beam and visual inspection results. Table 4 shows the patient demographic data (age, weight, height and BMI) and exposure parameters (tube voltage (kVp) and tube current–time product (mAs) in all hospitals. Table 5 illustrates the patients ESAR (mGy) during certain diagnostic radiography procedures. Wide variation was detected for patient doses in this study compared with previous studies and dose reference level. Patient doses in lumbar spine examination were higher than the doses for the other organs.

| kVp | Measured kVp | Error % | Acceptable |
|-----|--------------|---------|------------|
|     | A  | B  | C  | D  | A  | B  | C  | D  | Yes | No |
| 60  | 60.5 | 59.7 | 59.2 | 63.5 | +0.4 | -0.2 | 0.67 | +2.8 | √   |
| 70  | 72.09 | 70.3 | 69.6 | 71.3 | +1.5 | +0.02 | -0.29 | +0.92 | √   |
| 80  | 77.00 | 80.8 | 80.04 | 84.5 | -1.91 | +0.48 | +0.02 | +2.8 | √   |
| 90  | 97.8 | 89.8 | 89.9 | 92.7 | +4.15 | -0.05 | -0.06 | +4.58 | √   |

| Equipment | A | B | C | D |
|-----------|---|---|---|---|
| Working   | √ |   |   |   |
| Light working | √ |   |   |   |
| Light edge clear | √ |   |   |   |
| Cross indication | √ |   |   |   |
| Cross centered | √ |   |   |   |
| Lead thyroid | √ |   |   |   |
| Lead apron | √ |   |   |   |

Table 4. Patient demographic data and exposure parameters in all hospitals

| Hospital | No | Age (year) | Weight (kg) | Height (m) | BMI (kg/m²) | Tube voltage (kVp) | Tube current – time product (mAs) |
|----------|----|------------|-------------|------------|-------------|--------------------|----------------------------------|
| A        | 62 | 41.9±15.4 (18.0-80.0) | 56.8±13.2 (19.0-85.0) | 1.57±5.1 (1-1.85) | 21.1±1.9 (18.0-25.0) | 57.8±8.9 (43.0-70.0) | 26.2±15.3 (30.0-80.0) |
| B        | 61 | 41.8±2.2 (16.0-82.0) | 54.1±13.5 (26.0-80.0) | 1.58±0.19 (1.2-1.9) | 21.4±1.8 (17.0-25.0) | 62.0±8.4 (47.0-75.00) | 11.2±6.2 (4.0-30.0) |
| C        | 34 | 46.8±15.7 (20.0-80.0) | 63.4±12.1 (35.0-88.0) | 1.7±0.15 (1.3-1.9) | 21.2±1.8 (18.0-25.0) | 60.2±10.9 (40.0-85.0) | 11.5±7.3 (4.0-35.0) |
| D        | 63 | 43.2±14.8 (20.0-76.0) | 63.2±10.6 (37.0-86.0) | 1.72±0.14 (1.4-1.9) | 21.2±1.6 (18.0-25.0) | 59.7±11.3 (40.0-85.0) | 36.2±23.8 (10.0-80.0) |
Table 5. Comparison between mean ESAK (mGy) in different examinations and previous studies

| Examination     | Present study | Martin et al. [30] | Suliman and Mohammedzein [13] | Babikir et al. [22] | Kepler et al. [17] | Henner [18] | Ciraj et al. [10] |
|-----------------|---------------|--------------------|--------------------------------|---------------------|--------------------|-------------|-------------------|
| Chest           | 0.40          | 0.2                | 0.3                            | 0.6                 | 0.3                | 0.2         | 0.2±0.14          |
| Lumbar spine    | 2.0           | 6.0                | 6.4                            | 4.0                 | 6.4                | 5.0         | 1.6±1.0           |

4. DISCUSSION

Diagnostic X-ray imaging gives the largest contribution to the population dose from man-made radiation sources. Patient doses from conventional radiography were given trivial concern due to its low value compared to international radiology and CT imaging. Since the frequency of the performed procedures has augmented and a connection was reported between radiation exposure and cancer incidence, more consideration has been paid to keeping the patient radiation exposure to a low value while maintaining the diagnostic information [1]. Therefore, measurements of patient doses and implementation of dose reduction strategies without loss of diagnostic accuracy are crucial. Regular quality control tests on radiographic X-ray machines are essential to ensure that the performance of X-ray machines are within the acceptable limits and to carry out an immediate corrective action if needed. All X-ray machines tested for tube potential accuracy kVp showed acceptable errors as illustrated in Table 2. The highest error value was reported in machine D. The accurate performance of the X-ray machines can be attributed to the fact that all these machines are recently installed and monitored regularly according to national QC program. The visual inspection results for certain X-ray machine parameters such as lights, displays, and mechanical locks was satisfying; as illustrated in Table 3. Unfortunately, no thyroid shield, gonads shields or lead aprons were available at any of the departments. Because at these departments, only simple diagnostic X-ray procedures were performed; shielding (lead apron) is required in pediatric imaging for comforters’ protection during the imaging procedure. Thyroid shield may be needed during skull X rays and gonad shield are required for patient protection during pelvis X rays. The co-patients were not protected again radiation exposure.

The main source of discrepancies during X-ray imaging is patient weight. In this study, patients’ weight and BMI are comparable to hospitals A and B (54.0 kg and 56.0 kg, respectively). A higher patient weight 63.0 kg was noticed at hospitals C and D as illustrated in Table 4. The tube potential (kVp) was comparable for all X-ray machines. A maximum variation of 9% was detected between all hospitals. The tube current time product (mAs) in hospitals B and C was identical but varied widely from those in A and D. A maximum variation of 300% was detected between machine D and machines B and C. Tube current has proportionally increased the dose.

Patient exposure factors in screen-film radiography (SFR) are based mainly on the patients’ characteristics: weight and BMI, because certain exposure values are required to create an adequate film density. Any radiation exposure substantially higher or lower will overexpose or underexpose, respectively.

Exposure factors selection also depends on film and screen speeds which are among the most significant factors is determining the amount of radiation that must be delivered to the receptor to form a useful image. The film speed (regular speed index =400) is important for machine A, because all other machines were equipped with CR systems. This is determined by the sensitivity (speed) of the film. The sensitivity or speed of a radiographic receptor is determined both by characteristics of the intensifying screen and the film. In general, films with different sensitivity (speed) values are available for radiographic procedures. The primary disadvantage in using high sensitivity film (600, or 800) is that quantum noise is increased i.e less detail with low radiation dose; while low film speed provides fine details [19].

Exposure factors in radiographic X-ray procedures are considered as a function of patient weight and body BMI. Therefore, image quality on plain radiographs is also severely limited by attenuation. Increasing the current and exposure time can improve image quality at the expense of increasing the radiation dose to the patient and cause motion artifact due to increased exposure times. As expected, the highest organ dose was measured during LS
procedure while the lowest dose was in hand procedure. The radiographic exposure factors are under the control of the operator except for those fixed by the design of the X-ray machine. There are two choices for focal spot: large and small. The large focal spot is used with high tube current and low time which is suitable for involuntary motion, such as chest X rays and abdomen while a small focal spot is suitable for static organs such as bone imaging (skull and extremities).

Table 5 shows the comparison of measured ESAK (mGy) among difference X ray machines. From the results obtained, there is a wide difference in patients' doses in the hospital considered for individual patients and for each projection, though the mean dose does not vary greatly from one projection to another. From Table 5, the highest ESAK (mGy) was also detected during LS procedure due to the high density bony structures: a problem increasing with high body weight, which necessitates higher exposure factors, especially in lateral view.

Table 5, which compares the obtained ESAK with previous studies, illustrates that there is wide variation between previous studies. The dose in this study is quite high compared with previous studies except the study of Ciraj [10]. This dissimilarity could be attributed to exposure factors and patient characteristics (weight and BMI).

All X ray machines in this study are manually controlled by the technologist according to individual patient characteristics. A range of exposure factors is provided by a senior technologist based on their experiences in image acquisition. For SFR in certain cases the technologist increases the exposure parameters to compensate the chemical processing conditions, which leads to avoidable patient doses. Maintaining effective chemical conditions is the right solution for proper image quality to ensure reliable processing.

In literature [20], patient dose from CR procedures are higher compared to SFR procedures. The increase in patient doses can be explained by the inadequate selection of technical parameters for exposure. The use of the high kVp technique accompanied by lesser mAs and sufficient beam filtration will reduce the patient entrance dose without compromising the diagnostic findings [21]. Significant dose reduction can be obtained by reducing the field size of the X ray beam or by using protective shields to restrict the primary radiation to required organs or tissues. Due to technology advancement, the patient radiation dose was decreased by 50% in last two decades. To maintain the dose reduction during the transition from SFR to CR, staff training and regular dose monitoring can improve practice while sustaining patient exposure [20].

Patient doses reported from radiology procedures show significant patient dose reduction due to the introduction of digital imaging technology with sensitive detectors. This advancement enabled practitioners to obtain very good image quality with low radiation doses, when appropriate exposure parameters are chosen. Digital imaging technology offers practitioner with a high image quality in view of the fact that it has a wide dynamic range (1 to $10^4$) and image enhancement balances for inaccurate selection of exposure parameters even if the patient radiation exposure is higher than needed. While in SFR, which has a limited dynamic range ($10^{1.5}$), the radiographic images point out if an inaccurate exposure factor is selected [14]. Other limitations of limitations of the SFR system include cost, storage and high retake rate. Swee et al. [15] reported that SFR provides good spatial resolution 2.5 to 15 lpm compared with CR images (2.5 to 5 lpm). To obtain the benefit from both imaging systems, staff awareness is crucial to overcome the limitations.

This study has some limitations, the radiation dose is measured during procedures and the results were not corroborated by image quality. Also, occupational exposure was not addressed also in this study. In addition, as the patient populations included patients who underwent planar radiographic procedures for a diversity of clinical indications and patient demographic data, which resulted in a large patients dose variation. Further studies are suggested to establish DRL for these radiographic procedures including direct digital radiography (DDR) systems.

5. CONCLUSION

Patient dose measurements were carried out for 9 diagnostic radiographic procedures performed in 3 CR machines and 1 SFR determents. Patient's doses showed wide variation due to patient characteristic, exposure factors settings, X ray machine features and processing type. Patient dose was comparable between all four
hospitals for SFR and CR systems and below the reported procedures. Patient doses are decreasing in conventional radiography due to the introduction of new advanced imaging technology. The results indicate that there are still possibilities for dose reduction without loss of image quality. Conventional radiography must be used with high level of training for medical staff due to dose and main kVp output. Patient dose measurements are important in order to define a local diagnostic reference level. All technologists should be well trained in patient dosimetry aspects in CR systems.

ETHICAL APPROVAL

The author hereby declares that all experiments have been examined and approved by the institution ethics committee and have therefore been performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki. All X ray procedures were performed for justified clinical conditions by a qualified medical doctor.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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