Assessment of Radiological Parameters and Patient Dose Audit using Semi-Empirical Model.

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ABSTRACT

Risk is associated with all human activities; medical imaging is no exception. The risk in medical imaging is quantified using effective dose. However, measurement of effective dose is rather difficult and time consuming, therefore, energy imparted and entrance surface dose are obtained and converted into effective dose using the appropriate conversion factors.

In this study, data on exposure parameters and patient characteristics were obtained during the routine diagnostic examinations for four common types of X-ray procedures. A semi-empirical model involving computer software Xcomp5 was used to determine energy imparted per unit exposure-area product ($\omega(z)$), entrance skin exposure (ESE) and incident air kerma which are radiation dose indices.

The value of energy imparted per unit exposure-area product ranges between 0.60and1.21X10-3JR-1cm-2 and entrance skin exposure range from 5.07 ± 1.25 to 36.62 ± 27.79 mR , while the incident air kerma range between 43.93µGy and 265.5µGy. The filtrations of two of the three machines investigated were lower than the standard requirement of CEC for the machines used in conventional radiography.

The values of $\omega(z)$ and ESE obtained in the study were relatively lower compared to the published data, indicating that patients irradiated during the routine examinations in this study are at lower health risk. The energy imparted per unit exposure- area product could be used to determine the energy delivered to the patient during diagnostic examinations, and it is an approximate indicator of patient risk.

(Keywords: radiological parameter, dose audit, energy imparted, entrance skin exposure.)

INTRODUCTION

The physical universe is composed of two components; these are energy and matter. These components interact with each other in most physical processes and these interactions may lead to exchange or conversion of one into another. In medical imaging methods, images are formed by interaction between energy and human tissue [1]. Radiation that is used in diagnostic imaging is a form of energy that moves through space from one object, the source to another object where it is partly absorbed (during interaction with body tissue) and partly transmitted.

The selective interaction of X-ray photons with the structure of human body produces the image; the image produced can be viewed and used for diagnosis. During the interaction certain energy is deposited along the path of travel of the X-ray, others are scattered or deflected from its original direction and deposits part of its energy. The nature of interaction depends on the energy of X-ray photon, the nature of the tissue and the thickness of the irradiated area in question.

The energy imparted to the patient during the passage of X-ray through the body is also known as integral dose. It is a measure of total ionizing energy deposited in the patient during a radiological examination. This may be used to quantify the patient dose in diagnostic radiology [2]. The energy imparted to the patient may be used as an approximate indicator of the patient risk [3]; or used to estimate the equivalent effective dose [4].

There are various methods of obtaining energy, these include; the use of depth dose data [5], Monte Carlo techniques [6] and the use of transmission ionization chambers. The use of transmission ionization chamber can generate energy imparted data from an exposure -area or air collision kerma area product [7]. The use of an exposure-area product meter does not take into account the patient thickness, and the incident beam may not totally irradiate the patient. However, a model of obtaining an estimate of energy imparted to patients undergoing radiologic examinations was developed by Gkanatsios and Huda (1997) [5]. This method is based on Monte Carlo calculations of energy imparted from mono-energetic photons [6] and made use of published diagnostic energy X- rays spectra. In this model the experimental measurement required for the computation include; the entrance skin exposure, X-rays beam qualities (kV and HVL), exposed area and thickness of the irradiated region of the patient.

These parameters may be readily measured or estimated [4]. The energy imparted to the patient generally depends on the X–ray beam quality, the field size (area exposed) and irradiation geometry. The calculation of energy imparted to the patient during radiological examinations provides another method for determining effective dose and it is therefore of vital importance in radiation protection dosimetry.

This study was aimed at assessing radiological parameters, computing the energy imparted per unit exposure area product and entrance skin exposure during routine X-ray diagnostic examinations in radiology departments of three Nigerian hospitals.

MATERIALS AND METHODS

The patient anthropometrical data such as age, height, weight, sex, thickness of the irradiated region, and exposure parameters were obtained during the routine X-ray examinations of 246 patients at three different hospitals located in three major cities in southwestern Nigeria namely; Osogbo, Ibadan and Ijebu–Ode. The three hospitals investigated include; one teaching hospital (LTHP), a private hospital (ADHP), and one state-owned hospital (SHP).

The three X-ray machines investigated are analogue installed at various times. The output of the X-ray machine (in mGy(mAs)$^{-1}$ at 80 kVp and distance of 100cm normalized to 10mAs [9, 10,11, 12, 13] using a factory calibrated US-made Victoreen X-ray test device (4000 m+ KV meter). The choice of normalization at 80 kV and 10mA s was made as the potential across the X-ray tube and the anode current are highly stabilized at this point [11]. The KV meter was obtained from the Department of Physics (DOP), University of Ibadan. The first- and second-half value layers (HVLs) were obtained at different peak tube voltage (kVp) used during the examinations for different filtration of each machine at anode angle of 17^{o} using Xcomp5 computer software (R. Nowotny, University of Vienna, Austria) running on the Windows platform. The data (kVp, total filtration, and anode angle) were manually entered into the software which displays the output in form of incident air kerma (in µGy) and entrance skin exposure (ESE in mR).

For a patient undergoing radiographic examination, the energy imparted to the patient is given by Equation 1 [5] as:

$$\varepsilon = \omega\,(z)\,x\,EAP \qquad \textbf{(1)}$$

where $\omega\,(z)$ is the energy imparted per unit exposure-area product (J/Rcm^{2}). It is defined as the energy imparted to patient of thickness, z for an X-ray beam with cross sectional area of 1cm^{2}, normalized to unit exposure (free in air) at the patient surface with no backscatter. Also *EAP* is the exposure-area product and it is the product of free-in-air exposure at the patient entrance surface and the X-ray beam area at the location with the inverse square correction included. The free in air exposure could be converted into entrance skin dose in air using Equation 2 [14]:

$$ESD_{air}\,(mGy) = FAE\,(mR)\,x\,0.00877\,x\,BSF \qquad \textbf{(2)}$$

where *BSF* is the backscatter factor which the European guideline suggested 1.35 for adult and 1.30 for paediatric radiography [15].

The values of the beam area used for different part of the body could be obtained from the size of the film used. This is because it is important to include the entire organ in the beam that would normally be irradiated for a particular type of radiograph [16]. For a constant X-ray tube voltage and patient thickness z, $\omega\ (z)$ is given by Equation 3:

$$\omega(z) = \alpha\ x\ HVL + \beta \qquad \textbf{(3)}$$

where *HVL* is the half value layer, while α and β are parameter of fit obtained through Monte Carlo simulation by Gkanatsios and Huda (1997) [5] and tabulated at different kVp and different patient thickness ranging between 5cm and 30cm. Lagrange interpolation method was used to obtain the values that were not tabulated. For a constant kVp and *HVL*, anode angle does not have significant impact on $\omega\ (z)$.

RESULTS

Table 1 shows the radiographic and output data of the three X-ray machines investigated during this study. The table indicates that the machine found in LTHP SHP were installed more than a decade ago.The filtration of ADHP and SHP fell below the minimum required standard of 2.5mm A1 for X-ray machine being operated at peak tube voltage above 70kVp [17,18,19]. The range of kVp used in conventional X-ray diagnostic imaging is between 50 kVp and 120kVp.

Table 2(a-m) gives the summary of technical data for Chest PA (pediatric, LTHP), Chest PA (adult, LTHP), Chest PA (adult, SHP), Abdomen AP (adult, LTHP), Chest PA (adult ADHP), Chest PA (adult, LTHP), Abdomen LAT (adult, LTHP), Abdomen AP (adult, LTHP), Head PA (adult, LTHP), Head PA (pediatric, LTHP), Chest PA (adult, SHP), Head LAT (pediatric, LTHP), and Neck AP (adult, LTHP) for some of the patient encountered at the three hospitals.

Table 3 gives a summary of the peak tube potential (kVp/first half value layer (HVL), entrance skin exposure, incidents air kerma and the energy imparted per unit exposure-area product.

Table 1: Radiographic and Output Data of the Three X-ray Units.

Hospital	X-ray Radiographic Machine	Year of Installation	Total filtration mm Al	Output (mGy/mAs)
LTHP	NeoDiagnomax	1982	3.0	78.54
ADHP	Aicoma	2005	1.0	55.84
SHP	GEC Appolo	1984	2.0	26.64

Table 2a: Summary of Radiographic Data used during Chest PA (Pediatric) Examination (LTHP).

Statistical Parameter	Patient thickness (cm)	Applied tube potential (kVp)	Focus to patient distance (fsd) (cm)	Total X ray beam filtration (mmAl)	Product of tube current and time (mA.s)	BM1 kg m^{-2}
Mean	13.72	57	97.87	3.0	10.44	18.54
SD	2.76	0.01	13.51	-	3.52	6.09
CV(%)	20.1	0.02	13.8	-	33.7	32.9
Max	19	67	130	-	25	38.58
Min	8	47	75	-	6	9.72
Sample size	27	27	27	-	27	27

Table 2b: Summary of Radiographic Data used during Chest PA (Adult) Examination (LTHP).

Statistical Parameter	Patient thickness (cm)	Applied tube potential (kVp)	Focus to patient distance (fsd) (cm)	Total X ray beam filtration (mmAl)	Product of tube current and time (mA.s)	BM1 kg m^{-2}
Mean	20.41	66.13	104.9	3.0	20.13	22.48
SD	3.25	8.45	15.85	-	12.50	4.10
CV(%)	15.9	12.8	15.1	-	62.1	18.2
Max	30	80	130	-	100	36.0
Min	12	16	55	-	8	14.2
Sample size	80	80	80	-	80	80

Table 2c: Summary of Radiographic Data used during Chest PA (Adult) Examination (SHP).

Statistical Parameter	Patient thickness (cm)	Applied tube potential (kVp)	Focus to patient distance (fsd) (cm)	Total X ray beam filtration (mmAl)	Product of tube current and time (mA.s)	BM1 kg m^{-2}
Mean	22.92	85.25	124.92	2.0	9 (constant)	25.96
SD	1.62	5.51	31.79	-	-	7.86
CV(%)	7.1	6.5	22.5	-	-	30.3
Max	26	90	157	-	-	48.31
Min	20	75	66	-	-	18.99
Sample size	12	12	12	-	12	12

Table 2d: Summary of Radiographic Data used during Abdomen AP (Adult) Examinations (SHP).

Statistical Parameter	Patient thickness (cm)	Applied tube potential (kVp)	Focus to patient distance (fsd) (cm)	Total X ray beam filtration (mmAl)	Product of tube current and time (mA.s)	BM1 kg m^{-2}
Mean	24.67	107.5	91.38	2.0	26.75	24.75
SD	3.5	9.57	6.05	-	13.84	3.92
CV(%)	-	-	-	-	51.7	15.8
Max	28	120	177.5	-	45	27.41
Min	20	100	47	-	16	19.10
Sample size	4	4	4	-	4	4

Table 2e: Summary of Radiographic Data used during Chest PA (Adult) Examinations (ADHP).

Statistical Parameter	Patient thickness (cm)	Applied tube potential (kVp)	Focus to patient distance (fsd) (cm)	Total X ray beam filtration (mmAl)	Product of tube current and time (mA.s)	BM1 kg m^{-2}
Mean	20.67	80	129.31	1.0	15 (constant)	21.83
SD	1.85	-	1.86	-	-	2.49
CV(%)	9.0	-	1.4	-	-	11.4
Max	25	-	13	-	-	28.00
Min	17	-	125	-	-	17.10
Sample size	43	43	43	-	43	43

Table 2f: Summary of Radiographic Data used during Chest PA (Adult) Examinations (LTHP).

Statistical Parameter	Patient thickness (cm)	Applied tube potential (kVp)	Focus to patient distance (fsd) (cm)	Total X ray beam filtration (mmAl)	Product of tube current and time (mA.s)	BM1 kg m^{-2}
Mean	25.55	70.73	96.09	3.0	22.27	22.94
SD	6.28	7.25	15.24	-	7.55	7.70
CV(%)	24.6	10.3	15.9	-	33.9	33.6
Max	33	90	114	-	40	40.99
Min	15	63	63	-	15	13.59
Sample size	11	11	11	-	11	11

Table 2g: Summary of Radiographic Data used during Abdomen LAT (Adult) Examination (LTHP).

Statistical Parameter	Patient thickness (cm)	Applied tube potential (kVp)	Focus to patient distance (fsd) (cm)	Total X ray beam filtration (mmAl)	Product of tube current and time (mA.s)	BM1 kg m^{-2}
Mean	34	85.33	68.66	3.0	150	27.03
SD	11.61	11.17	23.07	-	50.20	9.38
CV(%)	34.1	13.7	33.6	-	35.5	34.7
Max	48	100	111	-	200	38.54
Min	19	67	49	-	80	17.76
Sample size	6	6	6	-	6	6

Table 2h: Summary of Radiographic Data used during Abdomen AP (Adult) Examinations (LTHP).

Statistical Parameter	Patient thickness (cm)	Applied tube potential (kVp)	Focus to patient distance (fsd) (cm)	Total X ray beam filtration (mmAl)	Product of tube current and time (mA.s)	BM1 kg m^{-2}
Mean	22.7	76	60	3.0	130.5	24.38
SD	5.33	7.06	16.68	-	48.84	6.62
CV(%)	34.2	9.3	27.8	-	37.4	25.7
Max	34	90	110	-	250	39.35
Min	16	70	60	-	100	17.75
Sample size	10	10	10	10	10	10

Table 2i: Summary of Radiographic Data used during Head PA (Adult) Examinations (LTHP).

Statistical Parameter	Patient thickness (cm)	Applied tube potential (kVp)	Focus to patient distance (fsd) (cm)	Total X ray beam filtration (mmAl)	Product of tube current and time (mA.s)	BM1 kg m^{-2}
Mean	20.88	75.96	94.48	3.0	105.64	26.18
SD	2.93	6.13	14.21	-	19.30	6.83
CV(%)	14.0	8.7	15.0	-	18.3	26.1
Max	27	85	132	-	160	42.72
Min	16	67	67	-	82	18.25
Sample size	28	28	28	28	28	28

Table 2j: Summary of Radiographic Data used during Head PA (Pediatric) Examinations (LTHP).

Statistical Parameter	Patient thickness (cm)	Applied tube potential (kVp)	Focus to patient distance (fsd) (cm)	Total X ray beam filtration (mmAl)	Product of tube current and time (mA.s)	BM1 kg m^{-2}
Mean	20	66	72.6	3.0	76.8	12.13
SD	2.55	4.42	9.76	-	63.95	5.31
CV(%)	12.8	6.7	13.4	-	88.3	43.8
Max	24	70	85	-	160	16.64
Min	17	60	63	-	16	6.32
Sample size	5	5	5	-	5	5

Table 2k: Summary of Radiographic Data used during Chest PA (Adult) Examinations (SHP).

Statistical Parameter	Patient thickness (cm)	Applied tube potential (kVp)	Focus to patient distance (fsd) (cm)	Total X ray beam filtration (mmAl)	Product of tube current and time (mA.s)	BM1 kg m^{-2}
Mean	15.63	74.17	98.28	3.0	69.08	27.72
SD	2.80	10.74	19.00	-	31.70	8.44
CV(%)	17.9	14.5	19.3	-	45.9	30.5
Max	23	100	120	-	100	42.85
Min	11	60	66	-	10	18.25
Sample size	12	12	12	-	12	12

Table 2l: Summary of Radiographic Data used during Head LAT (Pediatric) Examination (LTHP).

Statistical Parameter	Patient thickness (cm)	Applied tube potential (kVp)	Focus to patient distance (fsd) (cm)	Total X ray beam filtration (mmAl)	Product of tube current and time (mA.s)	BM1 kg m^{-2}
Mean	13	63.75	72.75	3.0	68	16
SD	1.82	2.90	9.50	-	38.51	0.97
CV(%)	14	4.7	13.1	-	56.6	6.1
Max	15	67	87	-	100	16.64
Min	11	60	68	-	12	14.61
Sample size	4	4	4	-	4	4

Table 2m: Summary of Radiographic Data used during Neck AP (Adult) Examinations (LTHP).

Statistical Parameter	Patient thickness (cm)	Applied tube potential (kVp)	Focus to patient distance (fsd) (cm)	Total X ray beam filtration (mmAl)	Product of tube current and time (mA.s)	BM1 kg m^{-2}
Mean	12.26	69.75	90.75	3.0	27.5	28.21
SD	1.71	2.06	12.58	-	10.63	5.29
CV(%)	14.0	2.95	13.9	-	32.7	18.8
Max	14	72	104	-	40	35.99
Min	10	67	74	-	16	24.56
Sample size	4	4	4	-	4	4

Table3: Entrance Skin Exposure, Incident Air Kerma and Energy Imparted per unit Exposure Area Product for Different Radiographic Examinations.

Examination	Status	Projection	kVp/first HVL	Sample size	Entrance Skin Exposure (ESE) (mR)	Incident air kerma (µGy)	*W(z)* JR^{-1}cm^{-1} (x10^{-3})
Chest (LTHP)	Pediatric	PA	57.4/2.18	27	5.07 ± 1.25	43.93	0.60
	Adult	PA	66.8/2.51	80	6.18 ± 2.38	54.28	0.77
	Adult	LAT	77.3/2.65	11	8.26 ± 2.92	71.81	0.81
Abdomen (LTHP)	Adult	LAT	85.3/3.19	6	23.31± 17.4	265.45	1.18
	Adult	AP	76.0/2.84	10	13.53 ± 8.02	116.27	0.99
Head (LTHP)	Adult	PA	75.9/2.84	28	9.70± 3.82	85.16	0.99
	Pediatric	LAT	63.7/2.42	4	11.34±2.07	98.83	0.65
	Pediatric	PA	66.0/2.47	5	12.25±2.57	106.52	0.75
	Adult	LAT	74.2/2.78	12	9.49±5.85	114.51	0.83
Neck (LTHP)	Adult	AP	69.8/2.61	4	10.40±5.44	76.15	0.69
Chest (SHP)	Adult	PA	82.3/3.21	12	8.12±5.62	70.33	0.99
Abdomen (SHP)	Adult	AP	107.1/4.09	4	36.62±27.79	317.65	1.21
Chest (ADHP)	Adult	PA	80.6/3.00	43	5.55/1.52	46.69	0.93

DISCUSSION AND CONCULSIONS

Table 1 shows that both ADHP and SHP fell short of the standard requirement of 3.0mmAl filtration for the equipment operated with kVp greater than 70 kVp.The beam energy primarily depends on the kilovoltage selected and the amount of filtration in the beam. Keeping all other variables constant, the entrance skin dose will change as the square of the change in kVp. Therefore, higher kVp increases the average energy of the X-ray beam and its penetrating ability. The choice of higher kVp gives room for use of lower mAs, thus reducing the dose to the patient [8]. Inclusion of filtration (both inherent and added) according to the regulation stems from the fact that filtration preferentially absorbs the low-energy X-ray in the beam. The low energy X-ray (less than 40 keV) does not contribute to image formation but rather patient dose. Additionally, the added filtration serves to further increase the average energy of the beam that can reach image receptor [1]. Inadequacy of filtrations in the two hospitals implies additional patient dose burden.

Table 2 (a-m) is the summary of technical data and thickness of the irradiated region for different projections. The tables for different projections show variations in the thickness of irradiated regions. The variation in the thickness of irradiated regions necessitates the selection of appropriate exposure factor (mAs, kVp, fsd,) that match a given thickness. The choice of exposure parameters according to the thickness of the patient to be radiographed is very important in dose optimization. Table 2c indicates that a constant value of mAs was used in ADHP while Table 2e indicates that a constant value of kVp and mAs were used. The use of constant value of either mAs or kVp for patient of different sizes could lead to the production of suboptimal image which consequently lead to repeated examination and additional dose delivered to the patient.

In conventional radiography kVp is normally selected based on the part of the body being imaged so that it is high enough for adequate penetration but low enough to produce good contrast among the type of tissue based on different amount of attenuation of the X-ray beam. In the selection of technical factors, the 15% rule could be used. Although a constant value of mAs was used in SHP for chest PA (Table 2c), it is relatively lower than the published value of 16.9 mAs [21]. However, the practice of high value of mAs seen in Table 2g (column 6) with maximum value of 200 mAs is far from a good practice; since increasing the mAs increases the dose delivered to the patient. The use of low mAs technique may cause low optical density of radiograph and reduces patient doses without adversely affecting image quality. The intra and inter comparison of technical parameters used by different hospitals show variation within and among hospitals (evident from the standard deviation). These trends in indicate non standardization of procedures; as a result there is urgent need to educate technical staff on the factors that affect patient dose and methods of reducing the dose delivered to the patient (especially pediatric patient).

Column 7 of Table 2 shows the body mass index (BMI) derived from weight/(height)^2. It is a useful classification scheme for the size and shape of the patient. The highest BMI recorded in this work is 28.21 kgm^{-2} for adult while the highest value of BMI for the pediatric patient is 18.54 kgm^{-2}. This classification helps to determine the technical factor to be selected during diagnostic examinations for a particular patient. The value of BMI assists the radiographer to know whether a patient is overweight, underweight or of normal weight and to select the most appropriate technical parameters that produce the diagnostically acceptable image at low doses.

Table 3 shows a summary of the entrance skin exposure (ESE), incident and air kerma and energy imparted per unit exposure- area product for different radiographic examinations. The ESE, incident air kerma and HVL were obtained with a Xcomp5 software (R. Nowotny, University of Vienna, Austria). It is evident from the fourth column of Table 3 that HVL is kVp dependent.

The high value of ESE (mR) and the corresponding value of incident air kerma obtained in abdomen LAT (LTHP) and in abdomen AP (SHP) could be probably attributed to high value of mAs used by the radiographer during the examination (as indicated in Table 2g and 2h). Moreover, the use of relatively high value of mAs during pediatric examination requires review especially in developing country as Nigeria to ensure that low doses are delivered to the pediatric patient. This review is necessary since the risk of carcinogenesis is generally greater for children than for adults, and the genetic consequences of dose to the gonads in pediatric patients are also higher than in adult [22]. As a result of the increased radiation induced risk in pediatric patients, it is necessary that the exposure factors such as mAs, kVp and fsd be carefully selected to ensure that the justified dose is optimized. This is possible through education, change of attitude and supervision.

Involvement of Medical Physicist in Nigerian hospital during the radiographic examinations is essential. Earlier report shows that there are few medical physicists in Nigeria radiological departments [23]. Meanwhile, the values of ESE obtained in this study is relatively lower than the published values [21] by a factor of 37 and 16 in chest PA and abdomen LAT respectively. Similar trend is found in chest PA and head LAT. The disparity between the published value and the value obtained in this study could be as a result of the equipment used; exposure factors selected during examinations and experience of personnel. The comparison indicates that low doses are possible in developing country as Nigeria if appropriate exposure parameters are selected and used during examinations. Table 3 indicates that the value of ESE for pediatric patient is greater than the value for adult patient in head PA in the same hospital (LTHP).

The mean value of w(z) obtained in the study range from 0.60-1.21x10^{-3} mJ R^{-1}cm^{-1}. The highest value is found in abdomen AP (SHP), while the lowest is found in chest PA (pediatric patient) in LTHP. In addition, the w(z) obtained in this study is the starting point for the computation of energy imparted to patient as in Equation 1.

The energy imparted to patient undergoing a radiographic examination may be used for the accurate determination of patient effective dose especially when specific organ dose values are not of interest. The calculation of energy imparted with the use of exposure area product (EAP) and w(z) provides a reliable starting point for the estimation of effective dose from radiologic examination for which dosimetric data are not provided by NRPB [8]. Effective dose is a dosimetry parameter which takes into account the dose received by all irradiated radiosensitive organ and may be taken to be measure of stochastic risk. Therefore, the knowledge of *W(z)* helps in the determination of effective dose and hence the risk due to radiologic examination.

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