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A parametric model for estimating X-ray tube output using exposure factors

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Abstract

It is expected that radiation doses delivered to patient be regularly measured in every hospital and compared with the diagnostic reference levels (DRLs). This is to ensure compliance with the directives of the regulatory bodies. However, this measurement is difficult and costly in some developing countries. The difficulty could be attributed to the lack of facilities required to carry out both quality control test and dose measurement. This paper presents a way of calculating the output of X-ray machine and the dose delivered to the patient during diagnostic examination at any hospital using exposure parameters. This is based on model proposed by two earlier researchers. X-ray tube outputs calculated using this method was compared with the measured values.

Keywords: X-ray-output, quality control test, entrance skin dose, effective dose, exposure factor

1.0 Introduction

In recent times there have been advance in magnetic resonance imaging and ultrasound techniques; however, X-rays have maintained a key role in the diagnosis of disease in both developed and developing countries [1, 2]. As a result of extensive uses of X-rays, it became the largest man-made source of ionizing radiation to the general public [3, 4, 5]. Apart from the positive application of X-rays, it is known to cause biological injury to human and some injuries have been reported[6, 7]. Moreover, as a result of the risk involved in X-ray examinations it is usually recommended to keep the patient exposure to X-rays as low as reasonably achievable (ALARA) and at the same time maintaining the image quality [8].

In an attempt to protect the public and the personnel from being exposed to unnecessary radiation, the radiation protection system has been advocated and is expected tobeput in place in every hospital. The radiation protection in diagnostic radiology is governed by principles of justification and optimization, including the consideration of diagnostic reference levels (DRLs). A radiological procedure is justified if the benefits to the individual patient from the medical diagnostic obtained with the radiological image balance the individual detriment the exposure may cause. Once a medical exposure has been justified, the principle of optimization is applied-that is, the radiological examination must be carried out with equipment and exposure parameters that ensure doses to patients are as low as reasonably practicable, consistent with the intended diagnostic purposes [9, 10].

For effective radiation protection process, another important consideration is quality control (QC) of radiological equipment used during both diagnosis and treatment. QCprogramme involves selective testing of each major system component on a regular basis to ensure optimum performance within the system [11]. The major systems in diagnostic radiology concern X-ray production, X-ray detection, image processing and image viewing [12]. The operator of X-ray machine controls the quantity and quality of radiation with the KV, MAS, and exposure- time controls. If the equipment is not properly calibrated, or it is subject to malfunction, it will not be possible to control the radiation output. It can result in reduced image quality and unnecessary patient exposure, especially when repeat image is required. X-ray equipment is required to meet certain standard at the time of installation, and periodic calibration and quality assurance (QA) inspections are required.

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In addition to periodic checking of X-ray machine which are carried out as part of QA programme, it is recommended that an assessment of the individual doses delivered to patients be made at regular intervals [13, 14] to ensure compliance with accepted standard of practice. The method of determining patient doses involves measurement of the output of the machine, calculation of entrance surface dose (ESD) and conversion in to effective dose using published data. The ESD was recommended by InternationalAtomic Energy Agency [8]as the dose descriptor for guidance level in diagnostic radiography. Due to its simplicity and indication of the maximum skin dose, it is used for the periodic checking of patient doses[15]. On its part, effective dose is another descriptor that accounts for the absorbed doses and relative radiosensitivities of the irradiated organs in the patient and, therefore better quantifies patient risk [4, 16] which is the motivation for all patient dosimetry studies in diagnostic radiology.However, measurement of effective dose for any X-ray examination is tedious and time consuming.

Direct measurement of ESD could be done using thermoluminescent dosimeter (TLD)by placing it on the surface of the patient [17]. The effectiveness of TLDs is possible because they cannot be seen in the radiographic image and thus do not affect a clinical procedure. Additionally, the TLD discs are sensitive in all direction, therefore the dose value from TLD measurement include backscatter. Entrance Surface dose (ESD) could be calculated using machine output [in mGy$(mAs)^{-1}$] and technical factors such as voltage (kVp), product of current and time (mAs), focus to skin distance(FSD) and backscatter factor(BSF) based on either equation (1) or (2) [18, 19].

$$ESD = O_p \mathrm{x} \left(\frac{kV}{80}\right)^2 \mathrm{x} mAs \mathrm{x} \left(\frac{100}{FSD}\right)^2 \mathrm{x} BSF \qquad (1)$$

Where $O_p$is the tube output per m A s measured at a distance of 1 m from the tube focus along the beam axis, kV is peak tube voltage recorded for any given examination, mA s is the tube current-time product, FSD is the focus- to-skin (or patient) distance and BSF is the backscatter factor.

$$ESD = O_{p50} \mathrm{x} \left(\frac{50}{FFD - t_q}\right)^2 \mathrm{x} mAs \mathrm{x}\, BSF \qquad (2)$$

Where t_q is the sum of the patient thickness and the patient-to-film distance for a given examination$q$, O_{p50} is the radiation output [mGy$(mAs)^{-1}$] at 0.50 m from the tube focus at the tube potential used for the examination, BSF is the backscatter factor .

The use of analytical formulae as in equations (1) and (2) reduce additional work by the radiology department, facilitates extended dose studies to a much larger number of examinations that would be less cost effective than with thermoluminescence dosimeter(TLD) measurements It also enables the estimate of doses lower than the measurement sensitivity of the TLD and eliminates error associated with the interpolation of data from tables and graphs [20]. In spite of the effectiveness of this method of ESD estimation during the routine examination, the cost of obtaining the required facilities for output measurement at regular interval is rather on the high side in most developing countries. Besides, the inadequate care of the equipment leads in most part to equipmentdamage especially during transit from one place to another. However, the method described in this paper enhances easy calculation of doses delivered to the patients during routine examinations. The method used here is based on a mathematical model proposed by Robson and Harpen (14, 21) and output of the machine measured at various voltages.

The objective of this work is to report the calculation of radiation output of X-ray machines obtained from manipulation of mathematical model proposed by Harpen and Robson.The paper also demonstrates the application of the result obtained from the manipulation of the model to calculate ESD at different hospitals investigated. The work entails the use of output measured from various hospitals investigated to obtain the coefficients and exponents of mathematical model. The coefficient and exponent could be stored and used easily on excel spread sheet to calculate ESD in various hospitals, and thus determine the dose compliance with guidance level.

2.0 Methodology and Instrumentation

The investigation involves two major steps: the physical measurement and mathematical manipulation of both the model and data obtained from the measurement made. Measurement covered seven X-ray units located in two commercial cities in Nigeria: Kaduna (North -West) and Lagos (South-West). In Kaduna, the measurement was carried out in the Nigeria National Petroleum Corporation (NNPC) diagnostic centres (Rm1 and Rm2) while in Lagos, measurements were carried out in four hospitals (one general hospital, two specialist hospitals, and one military hospital) consisting of five X-ray units coded as GHLA (Rm 1 and Rm 2), PSHLA, NOHLA and NARHLA. Each of NNPCKA and GHLA has two functional X-ray units referred to asRm 1 and Rm 2 respectively. The measurement was conducted to check the suitability and safety of the facilities in the hospitals investigated. Part of the motivation for the study was to assess compliance of quality control test (QC) with the internationally acceptable standard. However, this analysis was aimed at examining an easy method for calculating output of the machine and dose delivered to the patient during the routine examinations.

Radiation output from X-ray tube is the amount of exposure in millirontgen (mR) delivered to a point in the centre of the useful X-ray beam at a distance of 100 cm (or 50cm as the case may be) from the focal spot for 1 mAs of electron passing through the tube. The output expresses the ability of the tube to convert electronic energy into X-ray exposure. This

parameter quantifies radiation yield [22]. Measurement of free-in-air-exposure, FAE (mR) was carried out using factory calibrated KV meter (US made Victoreen X-ray test device model 4000 M+) obtained from Department of Physics (DOP) University of Ibadan (UI). The consistency of X-ray tube output and the tube current (mA) were measured and reported elsewhere [23]. The tube current exposure-time product (mAs) and tube potential (kilovolt peak) were measured for the range of values used in practice (diagnostic examinations). The KV meter used during the investigations measures the mean, effective and maximum peak tube voltage, power phase, exposure and exposure time. KV meter determines the tube voltage with accuracy of ± 2% [24]. Theinternal ionization chamberof the KV meter that measures exposure has volume of 36 cm^3andit measuresthe exposure time to an accuracy of ± 2%. Moreover, the FAE (mR) measured is converted to output mGy (mAs^{-1}) by multiplying by a factor ≈ 8.77 x 10^{-3}/mAs [25], mAs in the denominator is the tube current-exposure time product set at the time of measurement of the output of the X-ray machine.

3.0 Theory

Conventionally, according to Harpen [21] and Robson [14] a mathematical model that relates the output of an X-ray tube in mGy$(mAs)^{-1}$ to the measured tube voltage is given by equation.

$$Output(O_p\ in\ mGy/mAs) = \alpha(KVP)^{\beta} \quad (3)$$

Where α andβ are constants (coefficient and exponent respectively) which depend on X-ray generator type, anode material, FSD and X-ray tube filtration. It could also be shown from the model that$O_p$is a function of kVp and mAs. *KVP* in equation (3) is the tube potential at which the output was measured. Taking the logarithm of both sides of equation (3) yields linear equation (4). The left hand side of equation (4), that is, $\log_{10}(O_p)$ is plotted against $log_{10}(KVP)$using EXCEL 2007 software.

$$\log_{10}(O_p) = log_{10}(\alpha) + \beta\ log_{10}(KVP) \quad (4)$$

Values of fitting coefficient α, and exponentβ were obtained from the first order curve of the form given in equation (4) fitted through the data using EXCEL 2007 software. These are shown inTable 1.

During the measurement of output other focus-to detector distance (FDD)may be used, however in order to correct the output for distances other than 100 cm, inverse square factor is required for correcting this [20] as in equation (5).

$$Output(O_p in\ mGy/mAs) = \alpha(KVP)^{\beta} \text{x } \left(\frac{100}{\text{FDD}}\right)^2 \quad (5)$$

Table 1: Values of coefficient α and exponent β in equation (4) for different hospitals

Hospital (X-ray Unit)	Coefficient (α)	Exponent (β)	R^2
GHLARm 1	1.18 x10^{-3}	1.991	0.931
GHLARm 2	1.09 x10^{-7}	2.701	0.981
NNPCKA Rm1	1.0 x 10^{-4}	1.367	0.982
NNPCKARm 2	1.12 x 10^{-5}	2.003	0.998
PSH LA	1.20 x 10^{-19}	9.510	0.998
NOHLA	1.20 x10^{-15}	6.888	0.994
NARHLA	1.57 x10^{-3}	0.976	0.999

4.0 Results and Discussion

Table 1 shows the results of values of fitting coefficient α, and exponent βobtained from the first order linear curve for different hospital (column 2 and 3), while column 3shows large value of R^2- coefficient of determination which shows the total variation in $\log_{10}(O_p)$ that is explained, or accounted for by the variation in $log_{10}(KVP)$. Results in this study show that extremely low values of α were recorded in two hospitals; PSHLA and NOHLA (1.20 x 10^{-19} and 1.20^{-15} respectively) and correspondingly high values of β . These values are higher than the valuesrecorded by [20] and the earlier proposed by Robson [14] and Institute of Physical Sciences in Medicines, [26] , that is, in the range of 2 to 3. It should be noted here that Robson used mammography unit in his study, this consist of low kV far below the value used in this present study (ie 25-32 kV). However the trend found in this study is in agreement with the value obtained in Owolabi et al. [20], that is, low value of α, resulted in relatively higher value ofβ.The value of the exponents obtained in GHLA Rm 2, NNPCKA Rm 2 fall within the range proposed by Robson[14] and IPSM [26] and the values obtained by Owolabi et al. [20]. Meanwhile the values of exponents obtained in GHLA Rm1 and NNPCKA Rm1 are below the range proposed in the literature[14, 20], it is also in agreement with some the values obtained for filtration between 1.0 and 2.0 mm Al. The variation recorded in this study could be attributed to the variation in the value of total filtration and the nature of the filter used.

5.0 Applications in Output and Dose Calculation

Next is the application of equations (3), (4) and (5) to determine the output of an X-ray machine even without the knowledge of filtration and anode angle. Application of this method enables the Physicistattached to the X-ray unit or any of the personnel saddled with the responsibilities of radiation protection and dose calculation as required by both local and

international regulatory bodies [27, 28, 29] estimate the dose delivered to the patient. This method is also cost effective because of hiring monitoring personnel is reduced. The following are the steps for calculating the output of an X-ray machine.

i. Measure the values of KVP for the range used in diagnostic radiology, that is, 50 to 140 kVp and the corresponding values of free-in-air exposure (FAE in mR) at about 10 mAs.
ii. Convert the FEA (mR) to output in mGy/mAs using≈8.77 x 10^{-3}/mA s , where mA s here the value of mA s is 10 mA s (as the case may be).
iii. Tabulate your value and obtain the logarithm of output and logarithm of KVP. Enter the value of both $\log_{10}(O_p)$ and $log_{10}(KVP)$ manually in a new EXCEL work sheet with the logarithm of KVP in column A (independent variable) and logarithm of output in column B (dependent variable).
iv. Highlight column A1 ……AN (N= 1, 2, 3….) and column B1……BN. Under the Chart type, select XY (scatter) and click on it. Click next until you get to finish. Place the cursor on any data point and right click from the pull down list, select Add Trendline, and click the trendline dialogue box appear. Under the Type tab select Linear, Display Equation on Chart, and Display R^2 value on the Chart. These actions produce the required graph and equation with the appropriate graph and the equation displayed.
v. In GHLA Rm 1 as an example, the linear equation is of the form:

$$Y = 1.991X - 4.928 \qquad and\ R^2 = 0.931$$

Comparing the displayed equation with equation (4), shows that

$\beta = 1.991\ and\ log_{10}(\alpha) = -4.928$

$$\alpha = 1.1803x10^{-5}\ by\ finding\ the\ antilog\ of\ log_{10}(\alpha) = -4.928.$$

vi Calculate the output of X-ray machine in GHLA Rm1 using equation (5) substituting the values

$KVP = 68.96\ kV, \alpha = 1.1803x10^{-5}, \beta = 1.991\ and\ FDD = 100cm.$ Using a calculator or Excel spread sheet and substituting the numerical values into equation (5), yields

$$Output = 1.1803\text{x}10^{-5}\ \text{x}(68.96)^{1.991}\text{x}\left(\frac{100}{100}\right)^2 = 0.05403mGy(mAs)^{-1} \pm 3.1\%$$

Vii To calculate ESD, we used equation (1) and the following values;

$KVP = 68.96\ kV, BSF = 1.35$ (for adult according to CEC, 1996),

$MAS = 10\ mAs, FSD = 90cm\ and\ O_p = 0.05403mGy(mAs)^{-1}$

$$ESD = 0.05403\ \text{x}\left(\frac{68.96}{80}\right)^2\ \text{x}\ 10\ \text{x}\left(\frac{100}{90}\right)^2\ \text{x}\ 1.35 = 0.669\ \text{mGy}$$

This is the value of entrance surface dose delivered to the patient at the skin surface where the X-ray beam enters the patient. It is a popular method of expressing patient radiation doses, this parameter does not take into account the X-ray beam quality[i.e. half value layer-HVL] or the size of the X-ray beam, therefore, generally is a poor indicator of the risk associated with a given radiographic examination [30]. However, it is used for determination of guidance level and could be converted into effective dose using data from NRPB R262 document [31].

Table 2 is theresult of two tails test carried out on the data collected from different hospitals investigated. The result indicates that there were significant differences betweenthe set voltage (kVp-set) and the effective voltage (kVp-effective) measuredin six out of seven hospitals. The exception of this is PSHLA. The significant differences observed could lead to excess dose being delivered to the patient. This error could be due to the machine used. The error could to some extent affect the diagnostic image produced during examinations.

Table 2: Test results of the significance difference between the measured and the set kVp using paired test(two tails) at confidence interval of 95%

Hospital (X-ray Unit)	P-value	Two tail-test	t-value	n	dF	md	r	95% confidence interval of the difference
GHLARm 1	<0.0001	Extremely sig	9.805	21	20	2.126	0.8922	1.674-2.579
GHLARm 2	<0.0001	Very sig	3.207	13	12	2.664	0.9984	1.609-8.434
NNPCKA Rm1	<0.0001	Extremely sig	6.196	12	11	-2.543	0.9926	-3.447-1.640
NNPCKARm 2	<0.0001	Extremely sig	24.176	18	17	2.664	1.0000	2.432-2.897
PSHLA	0.0601	Not quite sig	2.240	8	7	1.368	0.9998	-2.811-0.0764
NOHLA	<0.0001	Extremely sig.	204.16	7	6	-31.676	0.9971	-37.115- 356
NARHLA	0.0007	Extremely sig.	4.270	16	15	9.924	0.6655	4.190-14.378

Figures 1a to 1g show the comparison of X-ray tube output [mGy $(mAs)^{-1}$] measured (output/m) and the output calculated (output/c) at various voltages within the range used diagnostic radiology. The reason for the differences could be

attributed to the differences between the kVp-set and thekVp-measured. In figures 1a (NARHLA) and 1b (NNPCKA Rm 2) the calculated outputs are greater than the measured outputs at different voltages. However, in figures 1c (GHLA Rm 1) and 1d (GHLA Rm2), the results show that the radiation outputs measured are higher at lower voltages than the measured value, while the calculated outputs, are relatively higher than the measured values at higher voltages.

Figures 1e (PSHLA), 1f (NOHLA) and 1g (NNPCKA Rm1)indicate that the radiation outputs measured are greater than the calculated values for the range of voltages measured. The trend of the X-ray tube output shown in Figures 1a and1b indicatethat itis voltage and machine dependent if every other parameters like filtration, tube current- time product (mAs) and focus-to- detector distance are kept constant. This is why its measurement is required regularly during the QC test to ascertain its level of compliance with the recommended standard of practice.In most developing countries like ours, regularmeasurements are not carried out, perhaps due to the cost or negligence.

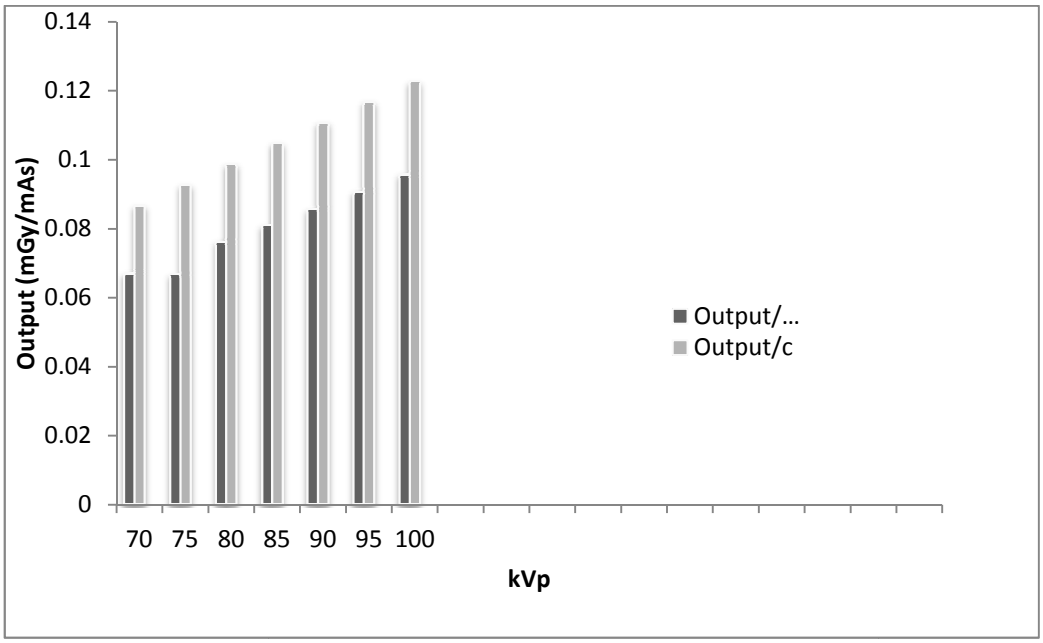

Figure 1a: Graph of Output (mGy/mAs) against kVp (NARHLA)

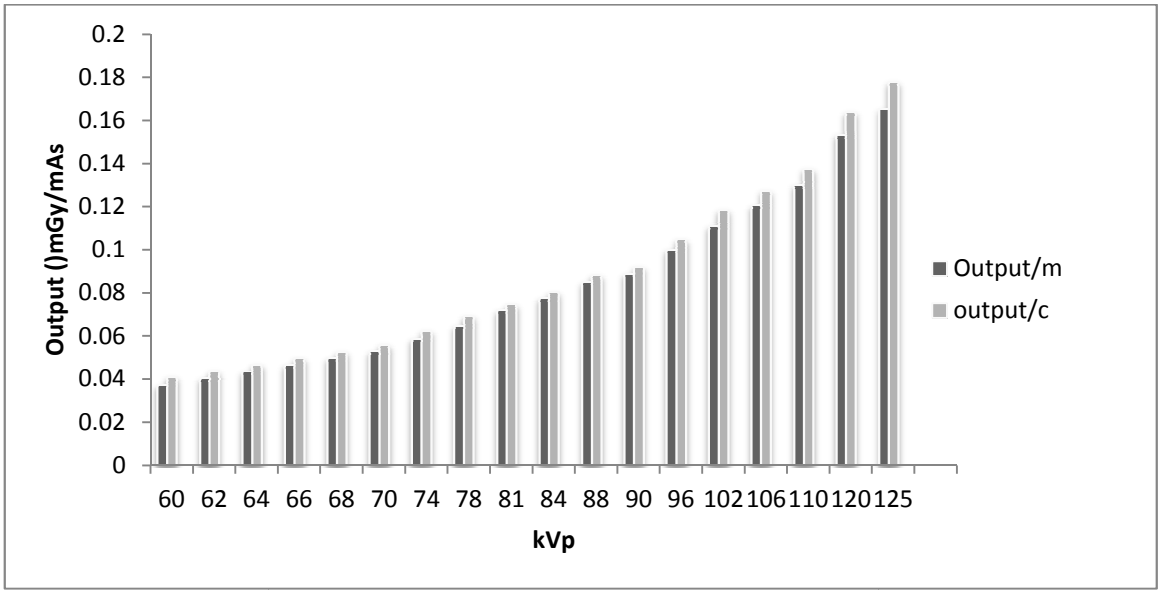

Figure 1b: Graph of Output (mGy/mAs) against kVp (NNPCKA Rm2)

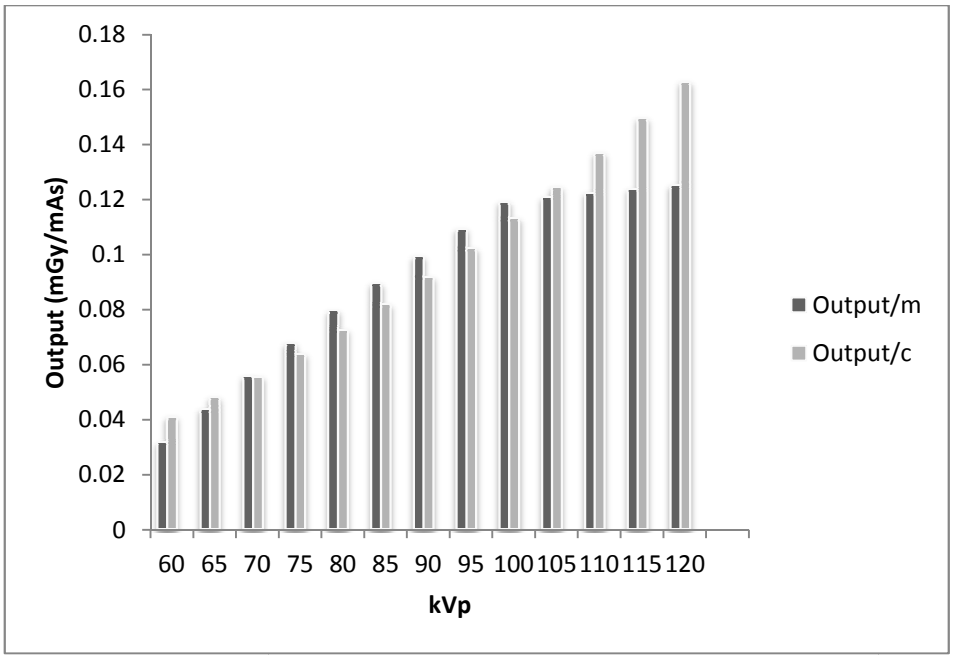

Figure 1c: Graph of Output (mGy) against kVp (GHLA Rm1)

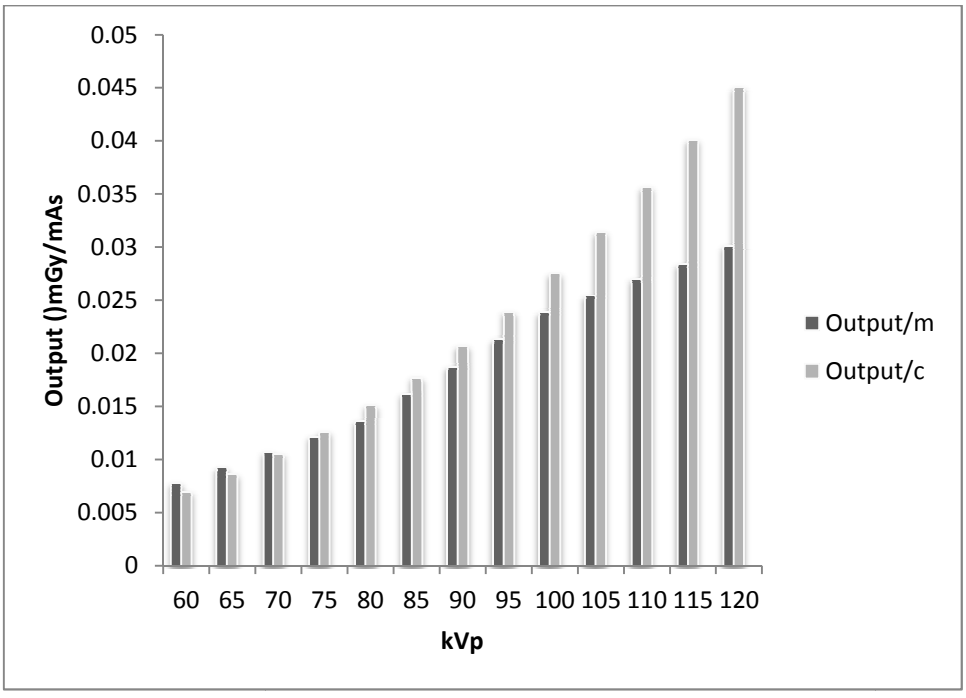

Figure 1d: Graph of Output (mGy/mAs) against kVp (GHLA Rm2)

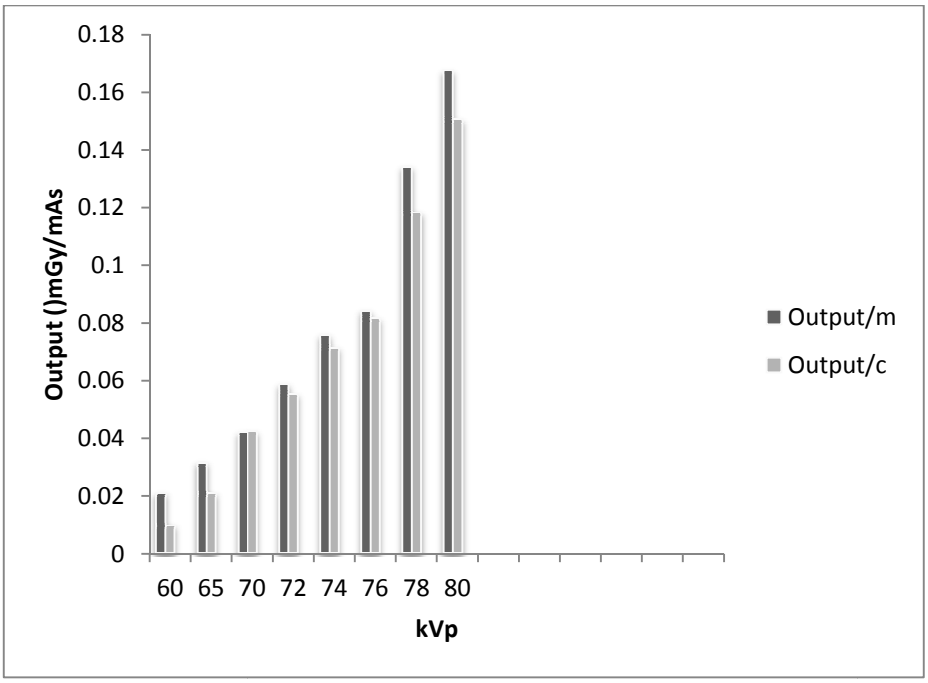

Figure 1e: Graph of Output (mGy/ mAs) against kVp (PSHLA)

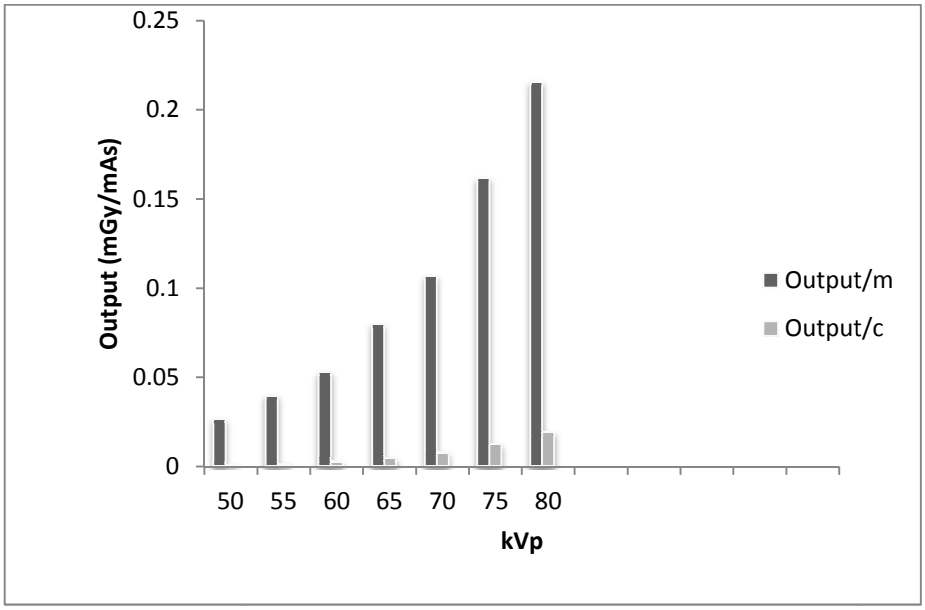

Figure 1f: Graph of Output (mGy/mAs) against kVp (NOHLA)

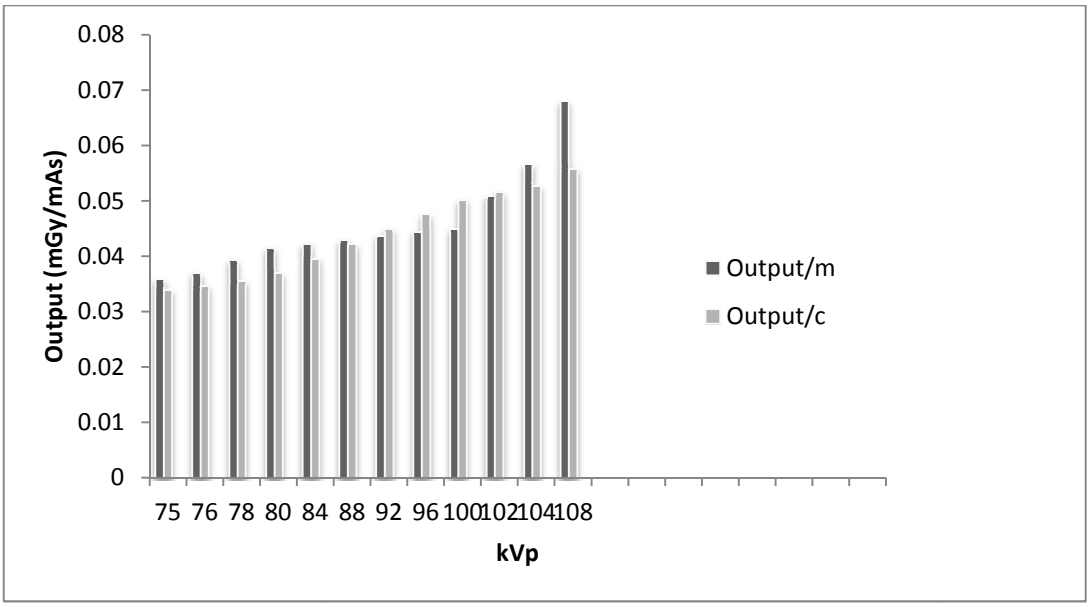

Figure 1g: Graph of Output (mAs) against kVp (NNPCKA Rm 1)

Figure 2 is a graph of ESD in air against mAs for five out of seven X-ray units investigated. Data for two units(NNPCKA Rm 1 and Rm 2) were not available for plotting. Available data show that the values of ESD increase rapidly in two out of the five X-ray machines (PSHLA and NOHLA)at about 35 mA s while the variation of ESD (air) with mAs is relatively small for GHLA Rm2. Moreover, there were slightly higher variation in NOHLA and GHLA (Rm 1) units.

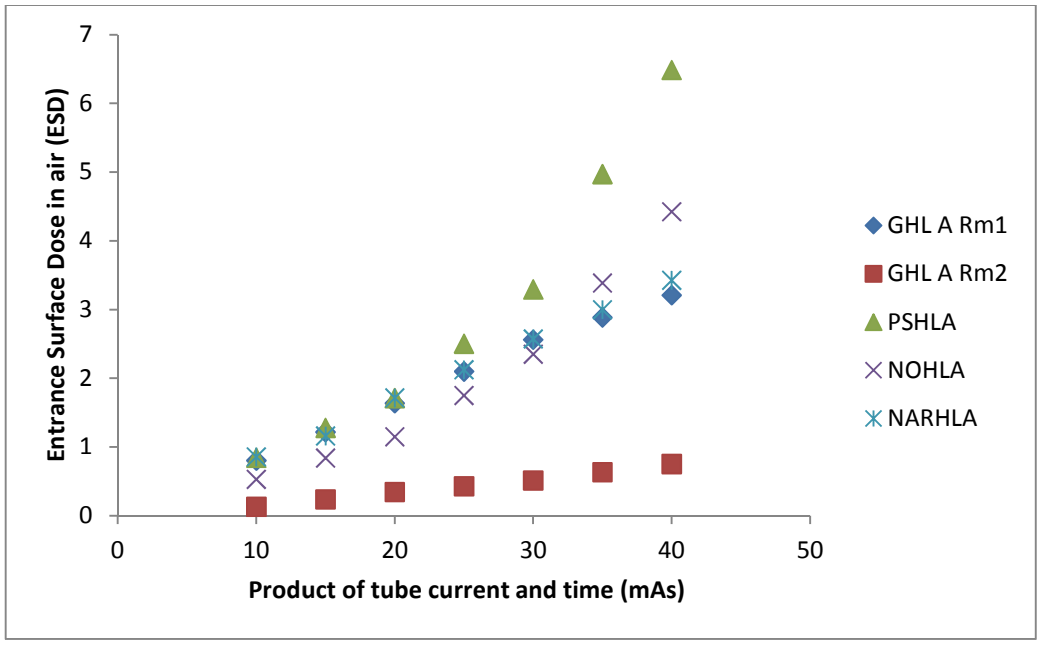

Figure 2 : Graph of Entrance Surface Dose (mGy) in air without backscatter against mAs

Thetrend here is an indication that ESD (air) is mA s dependent. It is therefore necessary that appropriate exposure parameter be used for patients of various sizes in order to get the doses delivered to the patient optimized while maintaining a diagnostically acceptable image.

Conclusion

Radiation dose (ESD) delivered to the patient is an important parameter which requires regular measurement to ensure that the justified examination is optimized, such that, quality X-ray services are rendered within the hospital. Regular dose monitoring and adjustment help to ensure compliance with the acceptable standard set by international and local regulatory bodies. Through regular quality control tests and dose measurement patients are protected from unnecessary radiation dose. Therefore, a system that could be used for easy calculation of dose delivered to the patient is necessary. The exercises in this study demonstrate that using the result from quality control test documented with the exposure parameters used during routine examination, the dose descriptor, ESD could be estimated. If the X-rays machine filtration, anode angle and collimator are kept constant, the exponent and coefficients calculated using data from the QC test could be used to estimate the tube output of a given machine, and hence calculate the ESD. Moreover, each time the QC test is carried out the data could be updated and compared with the existing data. This method is cost effective and could be used to estimate the ESD value below the minimum detectable value of TLD.

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