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KILO VOLTAGE MEASUREMENT OF X-RAY TUBE USING ALUMINIUM STEP-WEDGE

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ABSTRACT
The X-ray beam quality is expressed as kilovoltage. There are various methods for calibration of kilovoltage indicators including direct methods and indirect methods. But none is completely satisfactory. Tube potential produces both maximum energy in the photon beam and contributes to proportion of high energy photons also. Filter reduces the proportion of low energy photon and contributes to image on the film. In the present study, kilovoltage was determined by optical density produced on the exposed film and aluminium step wedge of varying thickness was used in the process. This method was easy, economical and efficient in all set ups. This was very reliable method for measurement of the kilo-voltage without using any major equipment. This gives the exact output and is more reliable when compared with the other methods.

KEYWORDS: Kilovoltage, X-ray, optical density, wedge.

INTRODUCTION
The kilovoltage across a diagnostic x-ray tube is generally indicated on the control panel of the generator by means of a voltmeter in the low tension circuit of the high tension transformer, or by means of numbered stud settings on the controlling auto-transformer. But these indicators have to be calibrated, and because a variety of methods are used for this, indicate that none of them to be entirely satisfactory. The open circuit kilo voltage from the transformer or, better the kilo voltage across the x-ray tube at a low tube current may be measured by the sphere gap method. The criticism of this method is that the voltage is not measured with the actual tube which is to be used with the transformer. The x-ray beam quality can also be expressed by means of the KVp and the filtration or the half value thickness (HVT) in millimeter of Aluminum. However, HVT alone is not a good indicator of beam quality for this purpose. A simple experiment can show that it is possible, with different KVp's and filtrations to produce x-ray beam with the same HVT, but which gives radiographs of quite different quality. HVT, is of course, valuable when KVp is known, particularly if similar wave forms are being considered. Peak voltage (KVp) can be sometimes be measured under working conditions. If the measurement is made by using a high resistance across the high voltage circuit, it is the RMS voltage which is actually observed. In practice not everyone has suitable equipment for measuring KV in clinical departments, as in any case it may be very difficult to make the measurement with generators in which the high tension circuit and x-ray tube are sealed in an oil insulated tank. Ideally all comparative measurement in diagnostic radiology should be made with a standard x-ray beam i.e. radiation from a tungsten target and generated at a true constant potential. One or the other complexities of these various methods of KV measurement requires the need for a method of voltage measurement which could be employed with equal facility in manufacturing unit or the hospital and which involve no disturbance of the apparatus in any way.[1,2,3]

In the present work, it is shown that the peak kilovoltage across x-ray tube may be determined by observing the threshold of some phenomena associated with the absorption of x-ray by the irradiated material. And it can be the optical density produced on the exposed film. The optical density of the film which is exposed along with the Aluminum step wedge of different uniform thickness placed on it and then studies the optical density of these various steps by the optical densitometer. The processing factor dependence of the exposed film is removed by taking the ratio of the optical density of the adjacent thickness produced on the film. The slope of the linear square fitted graph between the ratios of optical densities produced by adjacent steps of the step wedge on the film versus the corresponding KV applied provide the value of measured kilovoltage of the x-ray tube.

1.1 Measurement of Beam Quality Parameters

Radiation emitted by the x-ray tube is made up of photons of different energies. The maximum photon energy depends only upon the kilo voltage, while the minimum energy depends on the nature and thickness of the material of the wall of the x-ray tube and the filters used. Therefore we have to calculate the proper energy of the radiation beam to get the desired effect. The penetrating ability of the radiation is described as the quality of the radiation and it is specified by half-value layer or thickness (HVL). The HVL is the thickness of an absorber of specified composition required to attenuate the intensity of the beam to half its original value. In the diagnostic range of x-ray beam, the quality is described in terms of HVL as well as with KVp. But in case of megavoltage x-ray range, the quality is specified by the peak energy. The determination of x-ray tube potential is not easy because the high tension circuits of the most x-ray machines are sealed and therefore are not easily accessible for direct measurement. Therefore indirect methods are used to measure the KVp. However, directly measuring methods can also be used. Direct measurement methods include voltage divider method; sphere gap method. Indirect methods include fluorescence method; attenuation method; penetrameter; and by the study of optical density measurement using step wedge, generally Aluminum step wedge.[4]

1.2 Various Methods of Measurement Of Kilovoltage

Direct Measurement

a. **Voltage Divider:** The voltage divider is a circuit in which several high resistances are connected in series to form a resistance tower which is placed across the high-tension leads. The ratio of total resistance to the output resistance between two selected points gives the calibration factor, which when multiplied by the observed output voltage across those points gives the total voltage across the voltage divider.[1,2]
b. **Sphere-Gap Method:** In this oldest method, each high-voltage lead of the x-ray tube is connected to a polished metallic sphere by a cable adapter. The distance between the two spheres is reduced until an electric spark passes between them. By knowing the critical distance, corrected for air density and humidity, one can calculate the peak voltage across the x-ray tube.[2]

Indirect Measurement

a. **Fluorescence Method:** The fluorescence method is based on two principles. First, the peak photon energy is given by the peak potential. Second, K edge absorption is a threshold phenomenon in which K orbit fluorescence occurs when the photon energy is just equal to or greater than the binding energy of the K shell electron. Hence, by using materials of several different K absorption edges, one can calibrate the kVp dial on the machine.[3]
b. **Attenuation Method:** This method was described by Morgan[5] and, Newell and Henny.[6] It is based on the observation that the slope of the transmission curve of an x-ray beam at high filtration depends on the peak kilovoltage. The instrument is first calibrated by determining the ratio of the detector response with the two caps in place as a function of kVp of x-ray beams produced by a generator of accurately known peak potentials. Accordingly, an unknown kVp of an x-ray beam can be estimated from the calibration curve by determining the ratio of the detector response for the same two caps.[5,6]
c. **Penetrameter:** The operation of the penetrameter consists of comparing transmission through two materials with x-ray absorptions that change differently with photon energy. The original penetrameter was designed by Benoist[7] in 1901 and optimized by Stanton et al[8] in 1966. The central polyethylene block is surrounded on its sides by lead scatter shields, and metal step wedges. Aluminium wedges are recommended for the low kilovolt range and brass wedges for the higher kilovolt. For kilo voltage measurement, the penetrameter is radiographed in the beam with heavy filtration and scatter shielding. The optical density ratios of adjacent wedge and reference areas are used to obtain the matching step position. If the instrument has been calibrated against known potentials, the desired peak voltage can be read from the calibration curve.[7,8]

Another penetrameter is known as the Ardran-Crooks cassette.[9] This device consists of a film which is covered partly with a slow intensifying screen and partly with a fast screen. A copper step system is superimposed on the fast screen, while the slow screen is kept uncovered to serve as a reference. A sheet of lead allows only small (0.5-cm diameter) beam to pass through each copper step and the uncovered slow screen. When a radiograph is taken, the match of a step density with the reference depends on the kilo voltage. By using an appropriate calibration curve, one can determine the desired kilovolts. A commercial version of the Ardran-Crooks penetrameter is known as the Wisconsin Test Cassette.[9]

1.3 Tube Potential

The potential applied to the X-ray tube determines both the maximum photon energy and the proportion of high energy photons. The optimum potential will depend on the part of the body being imaged, the size of the patient, and the type of information required and the response of the image receptor. Using a higher tube potential results in poorer contrast and tends to produce more scatter, further reducing the image quality.[9]

1.4 Filtration

Thin sheets of metal such as aluminium or copper are incorporated into diagnostic X-ray tubes to reduce the proportion of low energy photons, as few are transmitted through the patient and contribute to the image. A filter equivalent to at least 2.5 mm of aluminium is incorporated as standard into medical X-ray tubes. Copper will absorb a higher proportion of the lower energy photons than aluminium. The disadvantage of using copper filters is that an increased tube output is required to compensate for the additional attenuation.[8,9,10]

1.5 Other Factors

a. Scattered radiation and use of low attenuation components

Radiation scattered from tissues within the body, increases the level of random background noise on the film and this degrades the visibility of low contrast details.[5,7]

b. Beam collimation and x-ray projection

Good collimation will both minimise the dose to the patient and improve image quality, because the amount of scattered radiation will increase if a larger volume of tissue is irradiated.[7,10]

1.6 Film Processing

When the film is developed, the affected crystals are reduced to small grains of metallic silver. The film is then fixed. The unaffected granules are removed by the fixing solution, leaving a clear film in their place. The metallic silver, which is not affected by the fixer causes darkening of the film. Thus the degree of blackening of an area of the film depends on the amount of free silver deposited and obviously, on the radiation energy absorbed. The degree of blackening of the film is measured by determining optical density with a densitometer. This instrument consists of a light source, a tiny aperture through which the light is directed and a light detector (photo-cell) to measure the light intensity transmitted through the film. If processing conditions are not optimal, the film will require a higher radiation dose in order to provide an acceptable film density. A system of quality control that involves checking temperatures of processing chemicals and carrying out sensitometry, involving development of a test strip of film exposed to arrange of light levels ensures optimal performance. These checks should be carried out daily to monitor performance in terms of film density, contrast and background fog level. The performance levels of processors that have a relatively low workload need to be monitored carefully. Since film processing affects the film density, it influences the speed index. Thus the measurements of the characteristic curve for a film will also reveal problems with processing.[10]

1.7 X-RAY Tube

The modern x-ray tube (Coolidge tube) is fitted in the gantry head of the simulator. The x-ray tube in operation has essential general features as under.[10]

a. **The Cathode** consists of a wire filament, a circuit to provide filament current, and a negatively charged focusing cup which directs the electrons toward the anode so that they strike the target in a well-defined area, the focal spot.

b. A **vacuum tube** with a facility to accelerate the produced electrons and to avoid the ionization of air or gas in it if present.

c. And a means to slow down the electrons suddenly called as **anode** having a high density material generally Tungsten metal. The focal spot becomes the source of bremstrahlung radiation.

1.8 Physics of X-Ray Production

There are two different mechanisms by which x-rays are produced. One gives rise to bremsstrahlung or braking x-rays due to result of radiative collision between a high-speed electron and a nucleus and the other characteristic x-rays which results from the inter orbit transition of electrons.[7,10]

1.9 X-Ray Energy Spectra

X-ray spectrum shows a continuous distribution of energy for bremstrahlung photons superimposed by characteristics radiation of discrete energies. The maximum energy in kilo electron volts is numerically equal to the applied kilo voltage peaks (KVp). The study of the present work reveals that the filtration affects primarily the initial low energy part of the spectrum and does not affect the high energy photon distribution. Therefore, with increase in the filtration, we get the hardened beam of x-radiations. Thus the additions of filtration and by increasing the voltage across the x-ray tube are the ways to improve the penetration powers of the beam.[5,10]

1.10 Rating for X-Ray Tubes

The high rate of energy deposition in the small volume of an x-ray target heats the target to a very high temperature. So, rotating anodes of high thermal conductivity are used to transfer heat rapidly to its surroundings. The induction motor is energized for about 1 second before high voltage is applied to the x-ray tube. This delay ensures that electrons do not strike the target before the anode reaches its maximum speed of rotation. X-ray tube rating charts include Energy rating charts, Anode thermal characterize charts, Housing cooling charts and Angiographic rating charts.[11]

Maximum Energy: Maximum energy ratings are provided for the target, anode and housing of an x-ray tube. These ratings are expressed in heat units, where for single-phase electrical power

Number of heat units (HU) = (Tube voltage) (Tube current) (Time) = (KVp) (mA) (sec)

If the tube voltage and current are constant, then 1HU = 1J of energy. For three-phase power, the number of heat units is computed as

Number of heat units (HU) = (Tube voltage) (Tube current) (Time) (1.35) = (KVp) (mA) (sec) (1.35)

2. Aim and Objective of The Project

The measurement of KVp can be studied by using a film to record the transmission of x-rays through an Aluminum step wedge. The degree of transmission is compared with KVp applied by measuring the transmission using an optical densitometer. Then the graphs are plotted for the various values of the optical densities with the applied KVp to get the value of unknown KVp.

3. MATERIALS AND METHODS

Procedure Conducted

1. The file (single coated mammographic films are used in the experiment from AGFA – HDR of size (8x10) inches) cut into half by the cutter and enveloped into a wrapper of EDR-2 in the darkroom.
2. Three range of kilovoltage are selected for exposing these films which are namely low KV range (mAs=320), medium KV range (mAs=160), and high KV range (mAs=100) which extends from 40KV to 100KV, 40KV to 110KV, and 80KV to 150KV respectively.
3. A ten-step aluminum test object with thickness ranging from 1mm to 5mm is used. Then the optical density of the film is measured at the center of each step of the wedge. The results are plotted.
4. The Aluminium (Al) step wedge is put on the packed film at a distance of 100 cm from the focus. The radiation field is collimated upto the size of the film.
5. These films are exposed for the above stated KV ranges at the three different fixed values of mAs that are milliampere seconds and the exposed films are developed within an hour with the auto processor (Protec automatic x-ray film processor) at the temperature 32^0 C to get the processed and dried film.
6. The optical densities are found out and recorded for each and every steps imprinted on the film. The Ratios of optical densities values are derived and tabulated for various kilovoltage ranges.
7. The graphs are plotted between the applied KV vs. optical densities at constant thicknesses, optical densities vs. thickness at constant KV and the ratios of optical densities of adjacent thicknesses vs. applied KV. These plots are used to derive the values of slopes and intercepts of the linear fitted lines.

   In this way, the result is interpreted from the graphs.

3.1 Simulator CT

The project work is performed on the machine of Simulator CT of model Phebus from Mecaserto equipped with an x-ray tube from GE manufacturing company, installed in the Radiation Oncology and Therapy department of Post Graduate Institute of Medical Education and Research, Chandigarh (India). The Simulator CT assists the radiation therapy team in the treatment planning process. Simulator CT has a diagnostic x-ray tube to duplicate geometrical, optical and mechanical properties of the treatment unit along with the verification of the diseased tissue in the body of the patient. All the information gathered during a simulation procedure such as treatment distance, field size and gantry angles must be reproduced as the therapy machine.[10]

X-ray generator in simulator: This provides radiographic and fluoroscopic control of the simulator. Because a single phase generator may limit the higher exposure factors needed for some examinations. The actual simulator CT machine used for the work has an extended facility for taking the tomography image that is an axial section of the body can be possible with this machine.[10]

3.2 X-RAY Film

Single coated mammographic film from AGFA- HDR of size (8 × 10) inches half are used for the project work, available in the department. These films are loaded in the envelope of KODAK- EDR2 ready pack envelope for exposing. These films are directly exposed without the use of any intensifying screens.[11]

3.3 Why We Choose The Aluminium Metal Step Wedge For This Purpose

Aluminum has it K- energy level at 1.6 KeV and it is well below the lowest photon energy in the spectrum used in the radiodiagnosis. And any characteristic radiation produced is very efficiently absorbed by air.

3.4 Specification of Aluminium Step Wedge

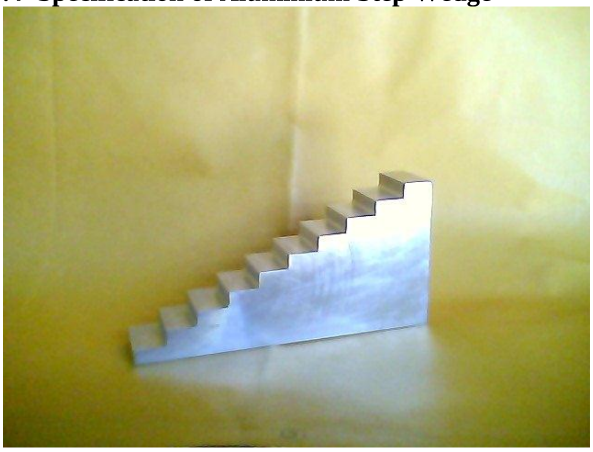


Figure 1: The original Aluminium step wedge used in the experiment.

Step size thickness = 5mm
Step length = 10mm
Step breadth = 20mm
Step wedge total thickness = 50mm
Step wedge total length = 100mm

3.5 Optical Densitometer and Optical Density

Digital Densitometer used for the experiment of the model named- DIGITAL DENSITOMETER; DM 5787 A. Optical densitometer determines the density of a sample placed between the light source and the photoelectric cell from differences in the readings. There are two types, Transmission densitometers that measure transparent materials and Reflection Densitometers that measure light reflected from a surface. In x-ray emulsions the radiation effect is measured in terms of the light opacity of the film. Opacity is defined as I_0 / I, where I_0 is the light intensity measured in the absence of the film, and I the intensity transmitted through the film in a direction perpendicular to its plane. The optical density (OD) is defined as $\log_{10}$ (I_0/I). The range of densities which is encountered in radiography runs from about 0.25 up to about 2.5. A plot of optical density as a function of kilo voltage or exposure or dose is termed as the sensitometric curve, or H-D curve. We should care for the film should be exposed in the linear region of the H-D curve. According the principle of operation of the densitometer, these can be spot, line and bi-dimensional densitometry.[12]

3.6 The Principle of Least Square Fittings

The aim of an experiment in any branch of science is either to verify an already known law or to look for some observations as curiosity and then find the law governing this. Thus, if the experiment gives measurement of some quantity y for different values of x; we get a set of n pairs of values of x_i and y_i having one to one correspondence. The problem of finding the functional dependence of the dependent quantity y on the independent quantity x viz, y= f(x) is known as curve fitting.

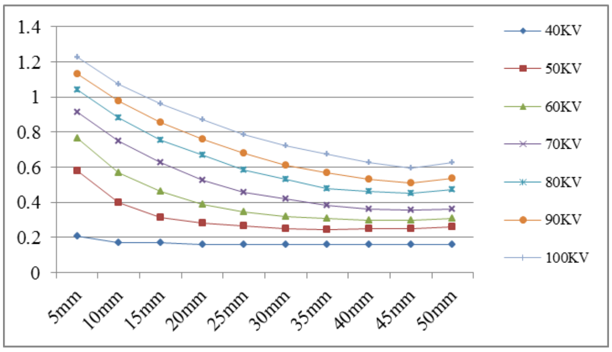
RESULTS AND OBSERVATIONS

From the data of optical densities observed in the Table 1, when plotted in graph 1 as optical densities vs various wedge thicknesses keeping the kilovoltage constant, it is observed that at low kilovoltage range (mAs=320) for a particular thickness, the optical density decreases exponentially and at 40 KV, this decrease is minimum and for 100KV in this range this decrease is maximum.

Table 1: Showing the OD values at different thicknesses for different KV.

KV	5mm	10mm	15mm	20mm	25mm	30mm	35mm	40mm	45mm	50mm
40	0.21	0.17	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
50	0.58	0.40	0.28	0.28	0.26	0.25	0.24	0.25	0.25	0.26
60	0.76	0.57	0.39	0.39	0.34	0.32	0.31	0.30	0.30	0.31
70	0.91	0.75	0.62	0.52	0.45	0.42	0.38	0.36	0.35	0.36
80	1.04	0.88	0.75	0.67	0.58	0.53	0.48	0.46	0.45	0.47
90	1.13	0.97	0.85	0.76	0.68	0.61	0.57	0.53	0.51	0.53
100	1.22	1.07	0.96	0.87	0.78	0.72	0.67	0.62	0.59	0.62

This is because at 40KV the energy of the photons is low as compared to the 100KV. This is because the photon beam obtained from the x-ray generator is not mono-energetic. And the higher thickness attenuates more as compared to the low thickness.



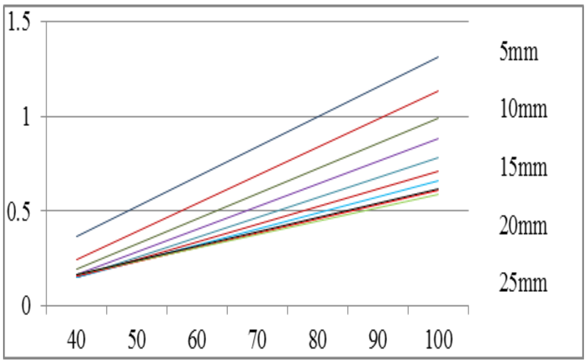
Graph 1: Plot between optical density vs different thicknesses at constant KVs.

If we plot the optical densities values vs Kilovoltage, keeping thickness constant, as observed in table 2 and graph 2.

Table 2: Showing the ratios of OD of adjacent thickness and different KV.

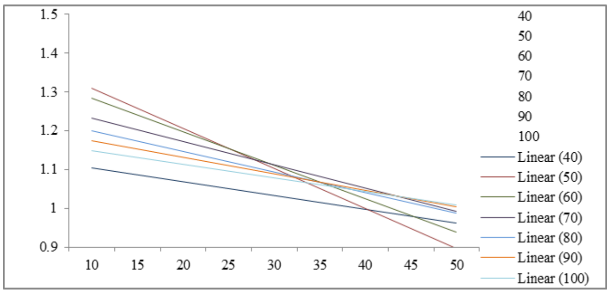
KV	10	15	20	25	30	35	40	45	50
40	1.235	1	1.063	1	1	1	1	1	1
50	1.45	1.27	1.125	1.057	1.06	1.02	0.98	1	0.962
60	1.342	1.226	1.192	1.13	1.078	1.032	1.033	1	0.968
70	1.22	1.2	1.19	1.154	1.083	1.091	1.069	1.014	0.986
80	1.182	1.166	1.127	1.145	1.104	1.104	1.043	1.022	0.947
90	1.159	1.14	1.125	1.118	1.115	1.07	1.075	1.039	0.953
100	1.14	1.12	1.103	1.108	1.09	1.067	1.08	1.05	0.952

It shows that the optical densities values increases as the kilovoltage increase for a particular thickness. This is because the higher energy photon can penetrate more easily which results in the higher optical densities values for a particular thickness. The slope is high for 5mm thickness pattern as compared to the others thickness. This is because of the fact that as the kilovoltage increases, intensity of the radiation beam increases and more number of photons penetrates through this thickness which produces more optical density on the film. But as the thickness increases from 5mm to 50mm, the slope of the line gradually decreases. Hence the optical density decreases for higher kilovoltage and high thickness. This is because most of the radiations are attenuated in the wedge material. And due to the effect of beam hardening that is less number of photons penetrate through the material and intensity decreases and most of photons are attenuated in the thickness. Therefore, only high energy photons penetrate through the material and produce some effect of optical density on the film.



Graph 2: Plot between OD vs applied KVs at different wedge thicknesses.

This pattern is clearly followed and represented in the graph 2, which is drawn from the observations given in the tables 1 for the low kilovoltage range (mAs=320). The percentage change in optical densities values for 5 mm filter thickness at 40 KV to 100 KV is 82% and it decreases to 74% for 50 mm. This is because with increase in KV the fluence rate of the photons obtained from x-ray generator increases; as a result the optical densities increases at fixed filtration thickness but optical densities values decreases simultaneously at higher thickness due to attenuation. In the Table 2, the thickness is normalized to adjacent thickness and we take the ratios of optical densities of the two adjacent steps. The plot of graph 3 is from the table 2, which is plotted keeping different kilovoltage constant. The linear fitted lines from the computer software shows that the values of the slopes of various lines are negative for all values but these are more positive as we compared to the previous values.



Graph 3: Plot between normalized step thickness vs ratios of OD of two adjacent steps (Low KV range).

Table 3 shows the slopes and intercepts for high KV range at mAs=320.

Table 3: Slopes and intercept for high KV range at mAs=320.

mAs=320		
KV	**Slope**	**Intercept**
40	-0.0036	1.14
50	-0.0103	1.412
60	-0.0086	1.37
70	-0.006	1.292
80	-0.0053	1.251
90	-0.0042	1.216
100	-0.0035	1.184

Similar observations were also taken for medium KV range (mAs=160) and high KV range (mAs=100) and the values are interpreted. Therefore, this pattern is followed by all the three ranges of kilovoltages. The slope and intercept are given in the table 3, 4 and 5.

Table 4: Slopes and Intercept for medium KV range at mAs=160.

mAs=160		
KV	**Slope**	**Intercept**
40	-0.00341	1.1342
50	-0.00767	1.3028
60	-0.00747	1.3332
70	-0.00762	1.3311
80	-0.00686	1.3514
90	-0.004951	1.2683
100	-0.00454	1.2552
110	-0.00283	1.2096

Table 5: Slopes and Intercept for high KV range at mAs=100.

mAs=100		
KV	**Slope**	**Intercept**
80	-0.0064	1.3092
90	-0.0063	1.2997
100	-0.0051	1.2612
110	-0.00414	1.2352
120	-0.00326	1.1972
130	-0.00281	1.1757
140	-0.00258	1.1691
150	-0.00207	1.1559

It is observed that the slopes are negative for low Aluminium filtration and becomes positive at high filtration thickness with gradual increase because at low thickness the x-ray photon obeys the exponential attenuation law. But with the increase in the filtration thickness the x-ray beam gets hardened and the slope increase and become positive.

VERIFICATION OF THE RESULT

Suppose we are to find out the exact KV for which the slope in the high KV (mAs=320) range is -0.0042. We can see that it lies between the 80 KV and 100 KV. Therefore, the interpolated value of KV from the table comes out to be 92.22KV. This is approximately equal to 90 KV (exact value). The error comes out to be 2.22 KV. The percentage error can be find out by the relation

Percentage Error = { (Actual value of KV – Calculated value of KV)/Actual value of KV}x100 = {(90 – 92.22)/90}x100 = 2.5 %.

DISCUSSION

This technique has the advantage that with the exception of the densitometer the apparatus required is extremely simple. As a photographic method of measurement is used to assess the conditions required in practice to produce a given photographic effect, there is automatic compensation for any reciprocity law failure that may occur when using screen-film combinations. There is also compensation for any lack of proportionality between tube out-put and milliamperes. The disadvantage of the method is that it is tedious and time consuming necessitating many tube exposures and using an appreciable quantity of films. It is not known until after the films have been developed whether the correct kilovoltage setting has been included in the range over which exposures were made. Furthermore, the milliampere-second have to be accurately controlled. In contrast, the ionization chamber method[11] gives a direct reading of the kilovoltage once the ionization ratio has been plotted against kilovoltage at low milliamperage, as would be done in an extended calibration. But this method requires more complex apparatus than the photographic method, and does not allow for any lack of proportionality between tube output and milliamperes.[13,14,15]

CONCLUSION

The method employed for kilo-voltage measurement of x-ray tube is easy, economical and efficient to be performed on both sites at clinical set up as well as in the manufacturing unit. This is very reliable method for measurement of the kilo-voltage without using any major equipment. This is absolutely electrical shock proof. The value of the kilo-voltage can be directly evaluated at various optical densities and (mAs) milliampere second. Also the values of (KV) kilo-voltage can be find out by the known value of slope by interpolation at a particular value of milliampere seconds for the three ranges of kilovoltages. It is a method which is performed totally in beam measurement of the kilo-voltage. This gives the exact output from the anode of the x-ray tube and more reliable as compared to the other methods. It is more comparable and reliable with the fluorescence method.

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