ESTABLISHMENT OF RQT BEAM QUALITY (100 TO 150 kV) FOR COMPUTED TOMOGRAPHY APPLICATIONS

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ABSTRACT: In Malaysia, the radiation beam qualities for calibration of dosimeters in computed tomography (RQT series) were established at the Secondary Standard Dosimetry Laboratory (SSDL) of the Malaysian Nuclear

Agency by using a constant potential industrial X-ray machine and a 0.6 cc PTW UNIDOS ionization chamber calibrated at the International Atomic Energy Agency (IAEA). Through the experimental method of additional filtration determination, the results demonstrated that all measured first half-value layer (HVL) filtrations (mm Al) for each RQT 8 (100 kV), RQT 9 (120 kV) and RQT 10 (150 kV) comply with tolerance limits of ± 3% as recommended by the IEC-61676. For RQT 8, a repeated experiment to determine accurate additional filtration has to be done with different added filtration RQT (mm Cu) thickness as the value initially goes beyond the 3% difference. Compared to prior radiation quality series RQT determinations, the added filtration for RQT 8 changed from 0.1 mm Cu in 2019 to 0.2 mm Cu in 2020. When compared against values established over the previous three years, all three RQTs for 2020 exhibit differences in measured first HVL filtrations (mm Al), albeit remaining within the 3% difference standard recommended in the TRS 457 standard of the IAEA. This change arises from x-ray tube ageing, anode roughening and inherent filtration alteration, leading to a perceived need for RQT trial and error re-evaluation to reduce the percentage decrement. Yearly monitoring of the beams should be performed to determine possible radiation quality changes, taking corrective action where necessary to remain within the prescribed tolerance limit. The standard radiation qualities should be maintained, allowing calibration accuracy to confirm dosimeter readings.

KEYWORDS: *RQT Radiation Quality; Malaysian Nuclear Agency; Dosimetry Calibration.*

1.0 INTRODUCTION

There is an undeniably increasing usage worldwide for medical imaging examinations, particularly in general radiography, fluoroscopy, and computed tomography (CT). In regards to the continuous emergence of the latest and advanced medical diagnostic equipment, the higher amount of radiation that the patients, radiographers, and medical workers are expected to receive directly or indirectly from these imaging procedures is becoming a primary concern. Even though the probability of radiation-induced malignancy caused by ionizing imaging tools is relatively low, the rise in per capita dose due to the growth in the number of individuals receiving these medical imaging examinations contributes to the need for controlled patient dosimetry [1]. In light of the significance of radiation dosimetry to the patients and the medical workers, the concept of dose optimization in accords to ALARA (as low as reasonably achievable) without jeopardizing the image quality has to be established together with regulatory control. Numerous codes of practice, written handbooks and technical reports have been issued globally to regulate radiology procedures and beam qualities by contributing to the establishment of Diagnostic Reference Levels (DRLs) such as the International Commission on Radiation Units and Measurements [2], International Electrotechnical Commission [3] and International Atomic Energy Agency [4].

The principle of DRLs was presented by the International Commission on Radiological Protection [5] and has been generally acknowledged as a practical means for dose optimization in medical imaging. DRLs should be applied as a method of investigation for patient exposure to identify unusually high dose levels. If DRLs are consistently exceeded, a local review normally ensues. As such, a review of patient dosimetry in a clinical setting is essential in terms of successful DRLs implementation. Direct dose measurement of radiation patients receive during medical imaging examinations is the initial step toward successful DRLs implementation. The measurements could be accomplished by means of radiation dose measured via dosimeters calibrated against a standard measuring system. It is essential that the used dosimeters were properly calibrated and accommodated in reference to IEC 61267 [3] and TRS 457 [4] as reference beam qualities for the calibration of instruments in medical imaging and radiology. Such calibration for the instrument is important as incident radiation is a major factor that can distort their energy responses [6].

The primary concept in establishing radiation quality for dosimetry calibration is to recreate a condition in which whilst it must be of a comparable environment to those encountered in routine use of the dosimetry instrument. In addition, it must be able to facilitate reproducible methodology between different dosimetry laboratories. According to Green et al. [7], the established form of calibration traceability regarding standard radiation dosimetry begins with the calibration of dosimeters by a Primary Standard Dosimetry Laboratory (PSDL). The same instrument and calibration setup are then used at the Secondary Standard Dosimetry Laboratory (SSDL) to reproduce the beam quality that closely matches the PSDL, to transfer the calibration from the Secondary Standard Dosimeter to a Tertiary Standard

Dosimeter. This Tertiary Standard Dosimeter is then used to define the radiation exposure for diagnostic instruments and dosimetry tools in which calibrated irradiations are to be tested in the clinical setting. Therefore, it is essential to establish radiation quality that is within the dynamic range used in real clinical practice. The quality of these instruments to measure X-ray outputs are critical for the upcoming valuation and patient doses regulator delivered by the hospital equipment. This article will discuss one of the established methods for precise calibration of dosimetry instruments in terms of investigating RQT radiation quality at SSDL in the Malaysian Nuclear Agency.

An X-ray beam spectra distribution for dosimeter calibrations had been discussed in detail by Green et al. [7-8]. The X-ray beam's utmost comprehensive description is characterized by its spectral distribution. To establish specific radiation quality, the portrayal of these beam qualities in the form of X-ray tube voltage (kV) and the first half-value layer (HVL) is normally applied since the spectrometry of X-rays necessitates a substantial amount of in-field competency, and it also takes longer duration to be accomplished. A concession amongst the equally inconsistent needs of evading extreme methodology to establish a radiation quality and warranting any uncertainty in the description of the radiation quality amongst many diagnostic imaging centres has led to the documentation of the standardized International Code of Practice TRS 457 [4].

Uncertainty in radiation quality in diagnostic imaging centres has led to the standardized International Code of Practice [4], the radiation qualities generated by X-ray tubes displaying inconsistencies in terms of tube age (with anode roughness and inherent filtration influences) and constructional differences (e.g., anode angle). This work concerns year-to-year changes in radiation quality. Malaysian Nuclear Agency has established a Secondary Standard Dosimetry Laboratory (SSDL), the national standard typically being referenced against the International Atomic Energy Agency (IAEA) primary standard, not least for calibration of dosimeters.

Table 1, including the listing of typical applications, concerns radiation qualities implemented for diagnostic imaging dosimeter calibrations. In line with TRS 457 [4], the beam qualities are established with reference to International Electrotechnical Commission IEC 61267 [3] recommendations. For measurement of the first HVL, the added filtration technique has been used, as documented by the International Commission on Radiation Units and Measurements [2]. This requires the use of a narrow-beam geometry to mitigate against in-scattering. The field incident on the ionization chamber (IC) must expose the entire IC for accurate measurement. At the Malaysian Nuclear Agency, a 2 cm diameter circular collimator is used, providing a field of 7 cm diameter at 100 cm source image distance (SID).

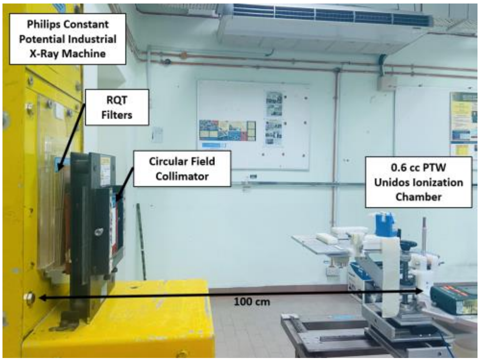
RQT radiation qualities that simulate the un-attenuated beam applied in computed tomography (CT) have been sought herein, determining the copper (Cu) filtration that may need to be added to the previously established RQR beam qualities. Annual assessment of first HVL filtration allows comparison against prior values, with corrections ensuring that differences do not exceed 3% [4]. Herein, a periodic establishment for RQT radiation quality at the Malaysian Nuclear Agency is detailed.

Table 1: Radiation qualities for calibration of diagnostic dosimeters [4]

Radiation quality	Radiation origin	Material of additional filter	Application
RQR	Radiation beam emerging from X-ray assembly	No phantom	General radiography, fluoroscopy and dental applications (measured free in air)
RQA	Radiation beam with an added filter	Aluminium	Measurements behind the patient (on the image intensifier)
RQT	Radiation beam with an added filter	Copper	CT applications (measured free in air)
RQR-M	Radiation beam emerging from X-ray assembly	No phantom	Mammography applications (measured free in air)
RQA-M	Radiation beam with an added filter	Aluminium	Mammography studies

2.0 METHODOLOGY

RQT beam quality measurements have been established at the Malaysian Nuclear Agency using a secondary standard 0.6 cc PTW UNIDOS ionization chamber instrument calibrated at the IAEA with Cu and Al filters of different thicknesses being slotted in front of a Constant Potential Philips Industrial X-Ray Model MG165 (Table 2). At the chamber's position, a field size of 7 cm diameter at 100 cm source image distance (SID) was established, obtained by slotting in a 2 cm diameter collimator in front of the added filters, ensuring a low scatter good geometry situation (Figure 1). The beam current and irradiation time were fixed at 5 mA for 50 s, respectively, applied for each radiation quality: RQT 8 (100 kV), RQT 9 (120 kV) and RQT 10 (150 kV). All the measurements for established radiation qualities had been performed in an air environment free of other perturbing materials, such as dosimetry phantoms, water, or other scattering materials. Temperature, pressure and relative humidity recordings were monitored and kept constant throughout the measurements.



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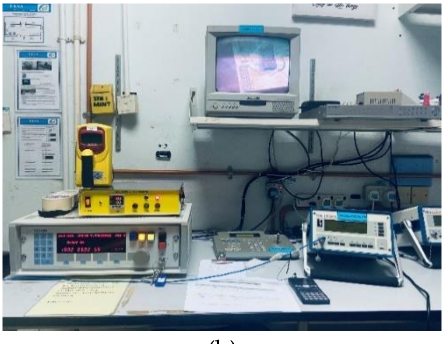

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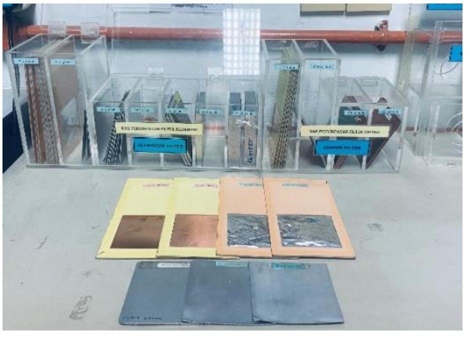

(c)

Figure 1: (a) Philips Constant Potential Industrial X-ray machine with filters aligned with 0.6cc PTW Unidos ionization chamber, (b) control panel at SSDL, Malaysian Nuclear Agency, (c) close-up of Al and Cu added filters

Table 2: RQT series for the period 2016 to 2019, within 3% agreement with IAEA values at the Malaysian Nuclear Agency

Radiation quality	X-ray tube voltage (kV)	Added filtration RQR (mm Al)	Added filtration RQT (mm Cu)	Total filtration RQR (mm Al) + RQT (mm Cu)	First HVL filtration (mm Al)	
					IAEA	Measured
RQT 8	100	3.7	0.1	3.7 + 0.1	6.9	6.7
RQT 9	120	4.0	0.2	4.0 + 0.2	8.4	8.4
RQT 10	150	4.8	0.2	4.8 + 0.2	10.1	10.1

Initial exposures were made in the absence of HVL filtration; the dose was recorded. In subsequent exposures, Al filters of different thicknesses were slotted in front of the collimator. Maintaining the initial technical factors, exposures were then made using different Al filter thicknesses. A linear graph of normalized dose against Al thickness was anticipated, allowing the first HVL filtration to be acquired via interpolation. HVL filtration must remain within 3% of that of prior years, with reference to the period 2016 to 2019. The RQT beam qualities were measured every year for the period 2016 to 2019, and the results for those four years were consistent. As referred to in Table 2, the measured results were in good agreement with the standard (IAEA) for both RQT 9 and 10, while the percentage of difference for RQT 8 was 2.89%, albeit within the acceptable range of 3%. For values exceeding 3%, trial and error use has been made of added Cu filtration, measuring the air kerma as before, with and without first HVL Al filtration.

3.0 RESULTS AND DISCUSSIONS

3.1 RQT 8 Additional Filtration Determination

As shown in Table 3, the determination of filtration for RQT 8 (100 kV) was initiated by slotting in RQR added filters, with 3.7 mm Al and RQT added filtration of 0.1 mm Cu, according to the previously established RQR beam quality maintained over the period 2016-2019 (Table 2). In the absence of HVL filters, the average dose is 15.1 mGy, as shown in Table 3. Subsequent HVL filters are then added within the recorded range of mm Al thickness for the first HVL filtration. A linear graph of normalized average doses against subsequent Al thicknesses is obtained (Figure 2). Concerning Figure 2, it is evident that the nominal first HVL filtration for RQT 8 is 6.2 mm Al, compared to the IAEA tabulated value of 6.9 mm Al. Beam hardening is evident, amounting to a decrease of 10.1 % in HVL value when referenced against the IAEA recommended value of 6.9 mm Al, exceeding the tolerance of 3%. This is suggested to be due to ageing of the x-ray tube, a manifestation of anode roughening and build-up of inherent filtration [4]. As such, RQT added filter (Cu) has to be added by trial and error, seeking to reduce the percentage decrement.

Table 3: Determination of additional filtration for characterization of radiation quality RQT 8

Radiation quality	X-ray tube voltage (kV)	Added filtration RQR (mm Al) + RQT (mm Cu)	HVL filter (mm Al)	Average dose (mGy)	First HVL filtration (mm Al)		Diff (%)
					IAEA	Measured	
RQT 8	100	3.7 + 0.1	0	15.1	6.9	6.2	10.1
			5.0	8.3			
			6.0	7.5			
			7.0	6.8			
			8.0	6.1			

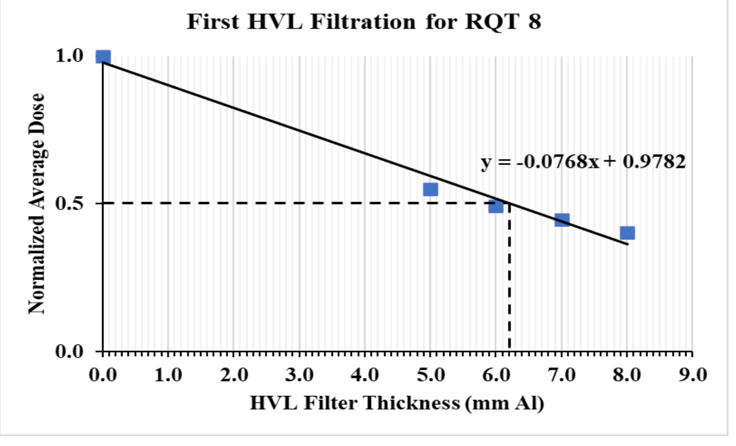

Figure 2: Measured first HVL filtration (mm Al) for RQT 8

Repeat determination of additional filtration for RQT 8 is shown in Table 4. RQR added filters of 3.7 mm Al thickness were slotted in front of the X-ray tube. However, instead of the previous use of 0.1 mm Cu, use has now been made of an increment of 0.2 mm Cu. With these new added filters, measurements were then made using the same technical factors as before, with values recorded in column 5, Table 4. As before, a linear graph of normalized average dose versus Al thickness has been obtained (Figure 3), allowing the first HVL filtration to be acquired, as represented by the dotted line in Figure 3. The new HVL filtration is found to be 6.9 mm Al (column 7, Table 4), being in accord with the recommended value of the IAEA [4]. The re-establishment of RQT 8 radiation quality at the Malaysian Nuclear Agency for the year 2020 has thus been obtained.

Table 4: Repeat determination of additional filtration for characterization of radiation quality RQT 8

Radiation quality	X-ray tube voltage (kV)	Added filtration RQR (mm Al) + RQT (mm Cu)	HVL filter (mm Al)	Average dose (mGy)	First HVL filtration (mm Al)		Diff (%)
					IAEA	Measured	
RQT 8	100	3.7 + 0.2	0	10.9	6.9	6.9	0
			5.0	6.6			
			6.0	5.9			
			7.0	5.5			
			8.0	4.9			

3.2 RQT 9 Additional Filtration Determination

A similar determination has been made for RQT 9 (120 kV), as referred to in Table 5. At 120 kV, using a constant 5 mA for 50 s, Table 5 shows close accord to have been realized within 3% of the IAEA nominal first HVL filtration of 8.4 mm Al. The linear graph of normalized average dose against Al thickness is shown in Figure 4. The measured first HVL filtration of 8.3 mm Al is shown in column 7, Table 5, amounting to a beam-hardening decrease in HVL of 1.2 %. Less than 3% change is deemed acceptable, with no repeat measurements necessary.

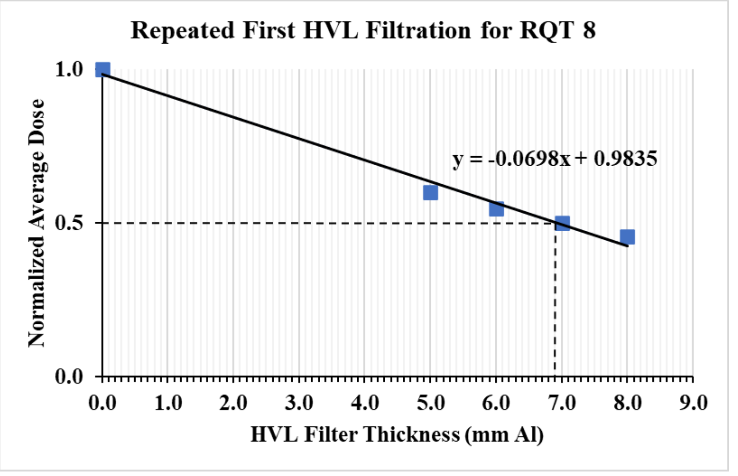

Figure 3: Repeated measurement of first HVL filtration (mm Al) for RQT 8

Table 5: Determination of additional filtration for characterization of radiation quality RQT 9

Radiation quality	X-ray tube voltage (kV)	Added filtration RQR (mm Al) + RQT (mm Cu)	HVL filter (mm Al)	Average dose (mGy)	First HVL filtration (mm Al)		Diff (%)
					IAEA	Measured	
RQT 9	120	4.0 + 0.2	0	17.1	8.4	8.3	1.2
			7.0	9.3			
			8.0	8.6			
			9.0	7.9			
			10.0	7.3			

3.3 RQT 10 Additional Filtration Determination

Finally, in Table 6, the record is made of RQR 4.8 mm Al added filters and RQT 0.2 mm Cu added filters, initially slotted in front of the x-ray tube to determine RQT 10 (150 kV). The reference IAEA first HVL filtration for RQT 10 is 10.1 mm Al [4]. In subsequent exposure, an HVL filter of total Al thickness of 9.0 mm was slotted in front of the collimator, the average of five readings being recorded, a step repeated for incremental Al thicknesses of total value 10-, 11- and 12 mm. Figure 5 shows a linear graph of normalized average dose against Al thickness. The calculated first HVL filtration of RQT 10 is 9.9 mm Al (column 7, Table 5). This amounts to a decrease of 2.0 % in HVL when compared to the reference value of 10.1 mm Al. As for the previous section, this change with respect to the prior value established at the Malaysian Nuclear Agency and the IAEA reference value is within the 3% tolerance. Re-establishing RQT 10 at Malaysian Nuclear Agency for 2020 is deemed successful with no change of added filtration RQR (mm Al) and RQT (mm Cu) thickness required.

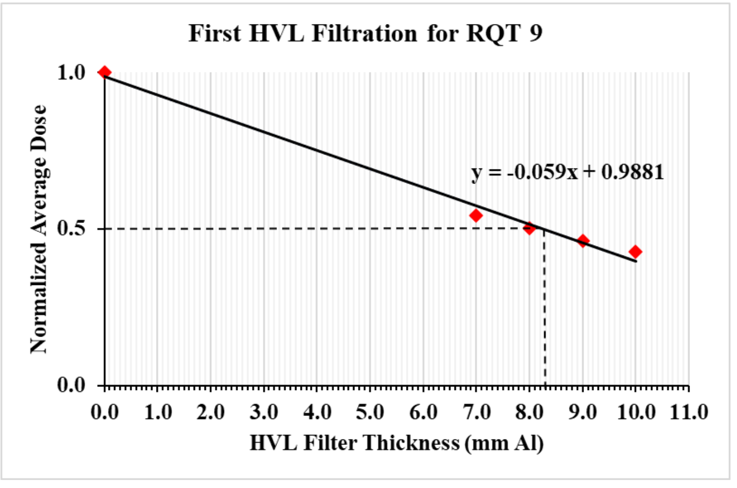

Figure 4: Measured first HVL filtration (mm Al) for RQT 9

Table 6: Determination of additional filtration for characterization of radiation quality RQT 10

Radiation quality	X-ray tube voltage (kV)	Added filtration RQR (mm Al) + RQT (mm Cu)	HVL filter (mm Al)	Average dose (mGy)	First HVL filtration (mm Al)		Diff (%)
					IAEA	Measured	
RQT 10	150	4.8 + 0.2	0	27.4	10.1	9.9	2.0
			9.0	14.0			
			10.0	13.2			
			11.0	12.4			
			12.0	11.6			

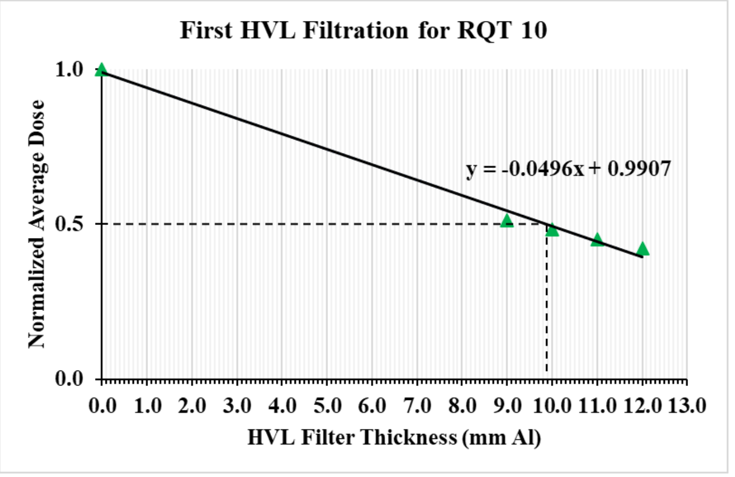

Figure 5: Measured first HVL filtration (mm Al) for RQT 10

3.4 Re-establishment of RQT Radiation Quality

Table 7 shows the final RQR (mm Al) total added filtration and RQT (in mm Cu), measured for the first HVL filtration. Compared to the RQT radiation quality series established from 2016 to 2019 at the Malaysian Nuclear Agency (Table 2), the added filtration for RQT 8 changed from 0.1 mm Cu in 2019 to 0.2 mm Cu in 2020. When compared against previous years, all three RQTs measured in 2020 differ from the baseline HVL filtrations (mm Al), nevertheless remaining within 3% of the recommended TRS 457 values [4]. In other words, the results demonstrated that all three measured RQTs' first HVL filtrations (mm Al) complied with the tolerance limits of ± 3% as recommended by the IEC-61267 [3]. The compliance of the results indirectly substantiated that SSDL in Malaysian Nuclear Agency is maintaining its standard of practice and quality control of periodic radiation quality establishment, particularly in sustaining the ageing of the x-ray tube, anode roughening and inherent filtration. Unsurprisingly, given the increasingly greater influence of the photoelectric effect as spectral distribution shifts towards lower energies, the change was greatest for the RQT 8 series.

Table 7: Re-establishment of radiation quality series RQT at Malaysian Nuclear Agency for the year 2020

Radiation quality	X-ray tube voltage (kV)	Added filtration RQR (mm Al)	Added filtration RQT (mm Cu)	Total filtration RQR (mm Al) + RQT (mm Cu)	First HVL filtration (mm Al)	
					IAEA	Measured
RQT 8	100	3.7	0.2	3.7 + 0.2	6.9	6.9
RQT 9	120	4.0	0.2	4.0 + 0.2	8.4	8.3
RQT 10	150	4.8	0.2	4.8 + 0.2	10.1	9.9

4.0 CONCLUSION

Periodic RQT radiation quality measurements have been performed at the Malaysian Nuclear Agency Secondary Standard Dosimetry Laboratory to calibrate dosimeters in CT applications. Use has been made of a Philips constant potential industrial X-ray machine supported by a 0.6 cc PTW UNIDOS ionization chamber calibrated at the IAEA. The results show that all three RQT first HVL filtrations (mm Al) comply with the ± 3% tolerance limit recommended in IEC 61267. For RQT 8, to provide for conformity, a repeat experiment was conducted to determine the additional filtration required to account for beam hardening of the x-ray tube. This new value may be due to the ageing of the x-ray tube in terms of anode roughening and inherent filtration. As such, an RQT added filter (Cu) must be added, obtained through trial and error, taking into account the percentage difference. Yearly monitoring on the first HVL filtration of the beams should be performed to test for changes with respect to prior values, seeking to maintain the accuracy of standard radiation qualities for calibrating diagnostic dosimeters, not least for CT applications.

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Education, Malaysia.

6.0 REFERENCES

[1] V. S. Panyam, S. Rakshit, S. D. Dhole et al., "Methodology adopted to establish diagnostic X-ray beam qualities", *Applied Radiation and Isotopes*, vol. 150, pp. 164-167, 2019.

[2] *International Commission on Radiation Units and Measurements, Physical Aspects of Irradiation*, *National Bureau of Standards Handbook*, ICRU, Bethesda, Maryland, 1964.

[3] *International Electrotechnical Commission, Medical Diagnostic X-Ray Equipment - Radiation Conditions for Use in the Determination of Characteristics*, IEC 61267, IEC, Geneva, 2005.

[4] *International Atomic Energy Agency, Dosimetry in Diagnostic Radiology: An International Code of Practice,* TRS 457, IAEA, Vienna, Austria, 2007.

[5] *Radiological Protection and Safety in Medicine. A Report of the International Commission on Radiological Protection*, ICRP 26, ICRP, Ottawa, Ontario, 1997.

[6] S. M. Tajudin, Y. Namito, T. Sanami, and H. Hirayama. "Photon field of ~100–200 keV for environmental dosemeter calibration", *Radiation Protection Dosimetry,* vol. 188, pp. 486-492, 2020.

[7] S. Green, J. E. Palethorpe, D. Peach, and D. A. Bradley. "Performance assessment of patient dosimetry services and X-ray quality assurance instruments used in diagnostic radiology", *Applied Radiation and Isotopes*, vol. 50, pp. 137-152, 1999.

[8] S. Green, J. E. Palethorpe, D. Peach, and D. A. Bradley. "Development of a calibration facility for test instrumentation in diagnostic radiology", *Radiation Protection Dosimetry,* vol. 67, pp. 41-46, 1996.