Establishment and Dissemination of Radiological Standards in the Field of Diagnostic Radiology in India

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Abstract

Background: The increased use of ionizing radiation for diagnostic purpose has resulted in an increase in the world population dose. Patient dosimetry in X-ray diagnostic radiology is required to establish diagnostic reference levels (DRLs) and to assess the average dose received by organs and tissues. International bodies have recommended DRLs to be based on dosimetric quantities. **Aim:** To cater to the increased requirement for dosimetry in diagnostic radiology, international guidelines are provided to establish and disseminate traceable calibration for dosimeters used in X-ray diagnostic radiology. X-ray diagnostic beams established are standardized using a diagnostic range free-air ionization chamber (DFAIC) (20-150 kV). **Materials and Methods:** Characterization of the DFAIC and determination of the correction factors for the air kerma measurements were evaluated experimentally and by theoretical calculations. **Results:** The paper details the establishment of 18 diagnostic beam qualities using DFAIC along with the associated uncertainties. The overall uncertainty for the air kerma measurements was within ±0.5% at 1 sigma level. Eight diagnostic range air kerma measurements using DFAIC were compared with the medium energy primary standard FAIC (50–300 kV) maintained in the laboratory. **Conclusion:** The air kerma rates agreed within ±1% and are within the overall standard uncertainty of both the chambers at the time of the comparison. Dissemination to the users in the field of diagnostic radiology in the country has been carried out by calibrating their ionization chambers and solid-state detector-based instruments against the DFAIC. The methodology followed to standardize the beams using DFAIC and calibration of dosimeters is presented in this work.

Keywords: Calibration, diagnostic radiology, free-air ionization chamber

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Introduction

The main component of the worldwide annual average dose from artificial sources of exposure is from medical diagnostic procedures. Since the early 1990s, there has been a significant rise (nearly 50%) in patients undergoing diagnostic medical examinations. With the advent of new and improved X-ray diagnostic tools such as computed tomography (CT), fluoroscopy, positron emission tomography, mammography, and other diagnostic tools, their use for diagnostic purpose has increased substantially.[1] Around 50% of the collective effective dose from X-ray diagnostic procedures is due to CT, interventional radiography, and angiography procedures.[2] It is observed that about 3.6 billion diagnostic X-ray examinations undertaken annually in the world.[1] To control the dose received by patients while undergoing diagnostic procedures, it is recommended internationally to apply the principle of optimization along with regulatory enforcement. Furthermore, it is imperative that the dose received by the patients should be measured using a calibrated dosimeter. Thus, there is an increased requirement to provide traceable calibration for instruments used in diagnostic radiology (CT, interventional radiology, mammography, and dental X-rays).[3-5]

ICRP 73, ICRU 74, ICRP-103, and IAEA BSS-2014 have recommended the establishment and use of diagnostic reference levels (DRLs) in diagnostic radiology.[6-9] DRLs are defined in terms of air kerma. Free-air ionization chamber (FAIC) is the

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primary standard to realize air kerma in the energy range under consideration. The FAIC is a wall less ionization chamber where the primary photon beam and the secondary electron interact only with air to realize the definition of exposure and air kerma. There are basically two types of FAICs used in standards laboratories worldwide – the plane parallel type and the cylindrical type. Majority of the laboratories in the world make use of the plane parallel type although there is some advantage of the cylindrical FAIC over the plane parallel type FAICs. The laboratory maintains a primary standard plane parallel type medium energy FAIC (MFAIC) for which international equivalence has been established by participating in international intercomparison programs. The experience gained in developing the MFAIC was made use in developing a low-energy FAIC having a plane parallel geometry.

The laboratory's FAIC (MFAIC) is designed for medium energy X-ray beams. It can operate over the energy range from 50 kV to 300 kV. Although in principle the use of MFAIC for low-energy measurements is possible, it is not recommended. The magnitude of the correction for air attenuation and scatter and its associated uncertainties are more when the attenuation length is large for low-energy measurements.[10] Many of the standard laboratories maintain two chambers – one for lower energy (up to 50 kV) and the other for medium energy X-ray measurements (50–300 kV). To carry out all the diagnostic range X-ray measurements using a single chamber, a FAIC was designed to be used in the diagnostic energy range of 20 kV to 150 kV. FAIC of similar dimensions meant for low energy measurements have been established by international standards laboratories.[11-14] The present study explains the design criteria of the chamber, characterization of the chamber, standardization of the diagnostic beams up to 150 kV, comparison with MFAIC of the laboratory, calibration of ionization chambers and X-ray meters, and evaluation of the associated uncertainties.

Material and Methods

Diagnostic range beam qualities established in the laboratory

The X-ray machine maintained in the laboratory is a YXLON MG325 make with tungsten target. Table 1 gives details of the diagnostic beam qualities and their possible applications. Diagnostic beam qualities-radiation qualities in radiation (RQR), radiation qualities based on aluminum added filter (RQA), radiation qualities based on copper added filter (RQT), and RQR beams for mammography (RQRM) were generated in the laboratory by determining the additional filtration required to generate the beams as per IEC 61267 and IAEA TRS-457 guidelines.[15]

Diagnostic range free-air ionization chamber

Parallel plate FAIC is a wall less ionization chamber which realizes the unit of the quantity exposure/air kerma from its definition. A schematic diagram of the diagnostic range FAIC (DFAIC) is shown in Figure 1 (a) along with the images of the chamber in open (b) and shielded condition (c). The chamber is enclosed in a lead-lined box having dimensions: 321 mm×210 mm×212 mm. The chamber enclosure is made up of lead sheet of thickness 5 mm sandwiched between aluminum plates of thickness 15 mm and 3 mm. The lead-lined enclosure is provided so as to ensure that no scattered radiation enters

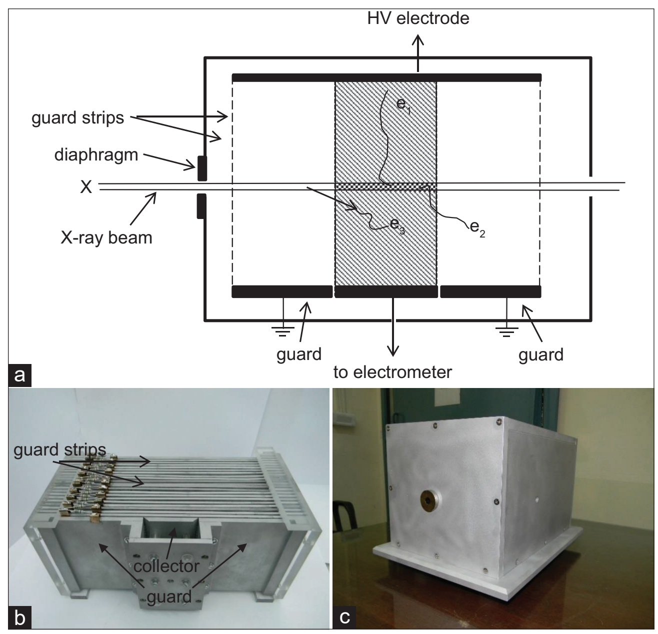

Figure 1: (a) Schematic diagram of the diagnostic range free air chamber developed (b) Chamber in open condition (c) Chamber in shielded condition. Electrons e1 represent those electrons which deposit all its energy in the collecting region before getting collected at the electrodes, electrons e2 and e3 represent electrons that compensate the loss of charge produced in the collecting volume by charge particle equilibrium

Table 1: Diagnostic radiation beam qualities for the calibration of diagnostic dosimeters

Radiation quality	Radiation origin	Material of an additional filter	Indication for possible applications
RQR	Radiation beam emerging from X-ray assembly	No phantom	Determination of attenuation properties of associated equipment
RQA	Radiation beam from an added filter	Aluminum layers	Measurement in the plane of the X-ray image receptor
RQT	Radiation beam from an added filter	Copper layer	Studies in CT applications
RQRM	Radiation beam emerging from X-ray assembly	No phantom	Studies in mammography
RQAM	Radiation beam from an added filter	Aluminum layers	Studies in mammography

RQR: Radiation qualities in radiation, RQA: Radiation qualities based on aluminum added filter, RQT: Radiation qualities based on copper added filter, RQRM: RQR-beams for mammography, RQAM: RQA-beams for mammography, CT: Computed tomography the chamber volume and also to attenuate the primary beam falling on the front wall of the chamber.

The basic component of the DFAIC is a tungsten diaphragm aperture and aluminum plates. The X-ray beam passes through the diaphragm and interacts with the air in the active volume of the chamber. The chamber consists of three coplanar plates parallel to a high voltage plate. The central plate is the collecting electrode, and the other two coplanar plates are the guard electrodes. DFAIC plates were fabricated using 5-mm thick aluminum plates of grade AL6061T6. Coordinate measuring machine was used to measure the dimensions of the collector plate, the guard plate, and the HV plate. It was also used to measure the coplanarity of the collector with the guard plates. The collector length is 50.0 mm (tolerance 10 µm), and the coplanarity and flatness of the plates were measured with a tolerance of 10 µm. The collecting electrode is connected to an electrometer to measure the current produced due to ionization in the volume of interest.

The energy range in which the DFAIC can be used is based on the concept of charge particle equilibrium (CPE) and the requirement that the electrode separation should be such that the secondary electrons generated by primary interaction of photons in air do not reach the electrodes. The chamber is designed such that the distance of the plates from the X-ray beam is greater than the range of the most energetic secondary electrons originating in the beam.

Plate separation distance was fixed at 10 cm based on the range of continuous slowing down approximation (CSDA) range of the electrons in air and Klein-Nishina energy transfer equation for Compton interaction. The CSDA value for 50 keV photon is 4.08 cm in air, and as the plate separation is 10 cm, energies lower than 50 keV will expend all its energy before getting collected. As the energy range under consideration is predominantly in the photoelectric region, correction for loss of electron before it expends all its energy is more for energies >60 keV. The distance between the diaphragm and the center of the collecting region is 13.88 cm which satisfies the CPE condition, and the correction for the attenuation in air of the low-energy photons between the diaphragm and the collector is not substantial.

Electric field is generated by applying polarizing voltage to the high voltage plate and the collecting electrode maintained at ground/virtual ground potential. The guard electrodes are also maintained at ground potential. Appropriate voltage is applied between the plates so as to collect all the ion pairs generated by the interaction of photons in the air volume of interest. The electric field perturbation in the FAIC is reduced by encircling the FAIC with horizontal guard strips with reducing potential across each strip.

The volume of interest is defined by the collecting electrode length, the electric field lines, and the radius of the tungsten diaphragm.

Air kerma is calculated by the given equation (1)

$$K_{air} = \frac{I \times \left(W/e \right) \times \pi_{ki}}{m_{air} \times \left(1 - g_{air}\right)} \qquad (1)$$

Where I is the current measured, W/e is the mean energy expended by an electron of charge e to produce an ion pair in air, m_{air} is the mass of air of the DFAIC volume defined by the aperture and the collecting plate, g_{air} is the fraction of initial electron energy lost through radiative processes in air, and Π_{ki} corrects for the ion recombination loss, air attenuation, air density change, polarity effect, photon scatter contribution, electron loss, and photon transmission.

While designing the tungsten alloy diaphragm, it was ensured that the diameter of the aperture is greater in diameter than the focus of the X-ray tube (5.5 mm for YXLON MG325 tube). The diaphragm's aperture was measured to have a diameter of 9.90 mm with a tolerance of 10 µm. Basic chamber properties are given in Table 2.

Characterization of diagnostic range free-air ionization chamber and evaluation of correction factor (experimentally)

Characterization of DFAIC and determination of correction factors, namely, ion recombination loss, air attenuation, air density change, polarity effect, photon scatter contribution, electron loss, and photon transmission were determined experimentally and explained in the following section.

Recombination correction factor k_s

For air kerma measurements, although the voltage applied to the ionization chamber is in the saturation region, ion recombination still exists for which correction has to be applied. In an ionization chamber, recombination of ion pairs is due to two processes – the initial recombination between oppositely charged ions in a single ionizing particle track and the volume recombination due to recombination of ions formed in different ionizing tracks which is a dose rate dependent quantity. To determine the ion pairs lost due to recombination, measurements were carried out with a low noise triaxial cable connected to the FAIC and the electrometer. The high voltage bias was applied through a separate voltage source. Saturation studies carried out show 99% saturation on the application of bias voltage of 400 volts and above.

Table 2: Geometrical characteristics of the diagnostic range free-air ionization chamber

Chamber Parameters	Dimensions
Aperture diameter	9.90 mm
Air path length	138.80 mm
Collector length	50 mm
Air gap length	5 mm
Electrode separation	100 mm
Collector width	120.10 mm
Measuring volume	3887.33 mm^3
Polarizing voltage	2000 V

The loss of ion pairs in recombination even after applying adequate bias voltage has to be corrected. Recombination correction factor was evaluated by the method described by Boutillon.[16,17] Ionization current I_V and $I_{V/n}$ of the FAIC were measured at two voltages, V and V/n where n is between 2 and 4. The ionization currents were corrected for change in temperature and pressure from the reference value. The measurements were repeated for different values of the air kerma rates by different filtrations. The ratio of the current $R = I_V/I_{V/n}$ was determined for the dose rate values standardized in the laboratory. The different values of R were plotted as a function of uncorrected ionization current $I_{V,\ uncorrected}$ (current which is not corrected for change in temperature and pressure, attenuation, etc.). The intercept of the linear fit of the data is denoted as a_0 and the gradient a_1.

The initial recombination coefficient k_{init} and the volume recombination coefficient k_{vol} are evaluated using the equations:

$$k_{init} = \frac{(a_0 - 1)}{(n-1)} \quad (2)$$

$$k_{vol} = \frac{a_1}{(n^2 - 1)} \quad (3)$$

The recombination correction factor k_s for the ionization current $I_{v,\ day}$ at polarizing voltage V on a given day is given by:

$$k_s = 1 + k_{init} + (k_{vol} \times I_{V,day}) \quad (4)$$

Where $I_{V,\ day,}$ is the ionization current for a particular day when a polarizing voltage V is applied for which k_s has to be determined. Linear fit curve for the determination of the ion recombination correction factor was plotted for the dose rates generated.

Linearity of response with variation of tube current of the X-ray tube

The response linearity test was done to verify that the DFAIC response is linear with dose rate variation. The tube current was varied between 1 mA and 30 mA. The measurements were carried out with constant voltage and additional filtration for beam quality RQR 5. The measured ionization charge was normalized to the charge corresponding to 30 mA tube current.

Polarizing correction factor k_{pol}

Polarity effect was studied by measuring charge with both positive and negative polarity and the polarity correction factor k_{pol} calculated as:

$$k_{pol} = \frac{|M_+ + M_-|}{2|M|} \quad (5)$$

Where M + and M_ are the charge obtained at positive and negative polarity, respectively, and M is the charge for the polarity routinely used. The polarity effect once determined is applied for subsequent measurements for each beam quality. The consistency of the value is checked at regular intervals to ensure that the value remains the same.

Air attenuation correction k_a

This correction is applied to correct the air attenuation between the reference plane and the center of the collection volume. The attenuation is determined by applying the mass attenuation coefficient in air for the effective energy of the beam standardized. The air attenuation correction factor k_a is given by:

$$k_a = e^{[(\mu/\rho) \times L]} \quad (6)$$

Where

μ/ρ is the mass attenuation coefficient (cm^2g^{-1})

L is the distance between the defining plane and the chamber center distance of 13.88 cm

The attenuation coefficient in air was taken from XCOM, published by NIST.

Air density correction factor $k_{T,P}$

This correction factor corrects for the change in mass of air in the collecting volume due to change in ambient temperature and pressure. The ionization current was corrected to get current at reference temperature of 20°C and reference pressure of 1013.2 mbar. The air density correction factor is given by equation 7.

$$k_{T,P} = \frac{(273.2 + t_{avg})}{(273.2 + t_{ref})} \times \frac{p_{ref}}{p_{avg}} \quad (7)$$

Where t_{avg} and p_{avg} are the average temperature and pressure values over the course of measurements.

Photon transmission correction factor k_1

The diaphragm used in the DFAIC is made up of tungsten alloy and has a simple cylindrical aperture. An analytical diaphragm transmission correction factor k_1[10,18] is used to correct for the transmission of photons through the downstream edge of the diaphragm and is given by:

$$k_1 = 1 - \left(\frac{2}{\mu Z}\right) \quad (8)$$

Where,

μ is the linear attenuation coefficient of the tungsten alloy for the effective energy of the beam and *Z* is the distance from the focal spot to the reference plane of the DFAIC. Diaphragm transmission correction factor for all the diagnostic beam qualities was determined and applied to the DFAIC measured current.

Transmission through front wall of the chamber

The beam interacts with the front wall having 5 mm thick lead sheet sandwiched between 15 mm and 3 mm of aluminum sheets. Measurements were carried out with the ISO narrow beam quality N100 to assure that the wall transmission is negligible for low-energy diagnostic range photon beams. Measurements were carried out with and without a suitable lead stopper in front of the aperture and wall transmission determined.

Electron loss correction factor k_e

Inadequate plate separation "*d*" and smaller collecting electrode width "*w*" results in the secondary electrons reaching the collector plate before expending all its energy which results in the definition of exposure not being realized. A correction factor to account for any loss of charge resulting from *d* and *w* is accounted in the electron-loss correction factor k_e.

The CSDA range for 55 keV electron is 4.81 cm in air. As the plate separation is 10 cm and the collecting electrode width is 12 cm, the electron loss correction factor for low-energy X-ray tube up to 50 kV is taken as 1. The percentage of electron loss for energies >50 keV outside a given radius from the X-ray beam was computed for a zero diameter beam in cylindrical coordinates and using the figures given by RITZ and NIST publications for additional filtration of 3 mm Al.[19-21] The electron loss corrections were determined up to 100 kV as a function of the half-value layer of aluminum and given by equation 9.

$$k_e = (1.00434) - [0.00426 \times (HVL\ Al\ mm)] + [0.00107 \times (HVL\ Al\ mm)^2] \quad (9)$$

Photon scatter correction factor k_{sc}

The collection of any charge due to the interaction of secondary photons in air is not to be included in the definition of air kerma. The correction factor for this contribution was calculated based on an empirical relationship given by Burns,[10,22] and the values of k_{sc} for some of the low and medium energy beam qualities were determined.

Air kerma measurements and comparison with MFAIC

Air kerma measurements were carried out with the DFAIC chamber for all the diagnostic beam qualities established in the laboratory. RQR beam qualities were compared with MFAIC for tube potential varying from 50 kV to 150 kV.

Results and Discussion

The DFAIC designed and developed in the laboratory satisfies the dual criteria of a FAIC – the attenuation length should be greater than the electron range for the maximum photon energy under consideration and the plate separation should be such that the secondary electrons expend all its energy before reaching either of the electrodes.

The first step in characterization of DFAIC was to determine the voltage at which all the ion pairs produced in the chamber are collected. Figure 2 shows measured ionization current as a function of applied voltage. Saturation of more than 99% is achieved when bias voltage of 400 volts and above is applied to the chamber.

Collection of all the ion pairs produced in the chamber volume is not possible as a finite amount of ion pairs is always lost to recombination. Recombination loss correction factor ks was determined for the dose rates generated in the laboratory by using the slope and intercept of the linear fit data plotted in Figure 3 and equations 2 - 4.

Application of 2000 volts and above results in an ion collection efficiency better than 99.96%. The linearity of response of the chamber with X-ray tube current is shown in Figure 4, and the linear correlation coefficient 0.99998 demonstrates the performance of the DFAIC with increasing dose rate.

Polarity and air density correction factor is determined and the DFAIC current corrected for it. Air attenuation

Table 3: Correction factors for the diagnostic range free-air ionization chamber for diagnostic beam qualities

Beam quality (kV)	Electron loss k_e	Photon scatter k_{sc}	Diaphragm transmission k_t	Air attenuation k_a	Product of correction factors $k_{product}$
RQR2 (40)	1.000	0.996	1.000	1.008	1.004
RQR3 (50)	1.000	0.997	1.000	1.007	1.004
RQR4 (60)	1.000	0.997	1.000	1.006	1.003
RQR5 (70)	1.001	0.997	1.000	1.005	1.003
RQR6 (80)	1.002	0.997	1.000	1.005	1.004
RQR7 (90)	1.003	0.997	1.000	1.005	1.005
RQR8 (100)	1.005	0.997	1.000	1.004	1.006
RQR9 (120)	1.005	0.997	1.000	1.004	1.006
RQR10 (150)	1.005	0.997	1.000	1.004	1.006
RQA2 (40)	1.000	0.996	1.000	1.006	1.002
RQA3 (50)	1.000	0.997	1.000	1.005	1.002
RQA4 (60)	1.005	0.997	1.000	1.004	1.006
RQA5 (70)	1.005	0.997	1.000	1.004	1.006
RQA6 (80)	1.005	0.997	1.000	1.003	1.005
RQA7 (90)	1.005	0.997	1.000	1.003	1.005
RQT8 (100)	1.005	0.997	1.000	1.004	1.006
RQT9 (120)	1.005	0.997	1.000	1.003	1.005
RQRM2 (28)	1.000	0.996	1.000	1.027	1.023

RQR: Radiation qualities in radiation, RQA: Radiation qualities based on aluminum added filter, RQT: Radiation qualities based on copper added filter, RQRM: RQRM: RQR-beams for mammography and diaphragm transmission correction factors were determined for the effective energies of the diagnostic beams. The transmission of photons through the front wall of thickness 5 mm lead for the DFAIC is 0.09%. It is generally recommended that the transmitted photons should be less than 0.1% of the initial beam.[23] Electron loss correction factor varied from 0.02% at 60 kV to 0.5% for 100 kV X-ray potential. For X-ray beams with tube potential higher than 100 kV and also additional filtration >3 mm, electron loss correction factor of 0.5% was applied as the calculations are based on RITZ and NIST publications for tube potential up to 100 kV and additional filtration of 3 mm aluminum. Photon scatter correction was <0.5% for X-ray potential up to 150 kV. Table 3 gives the correction factors applied to the DFAIC measured current.

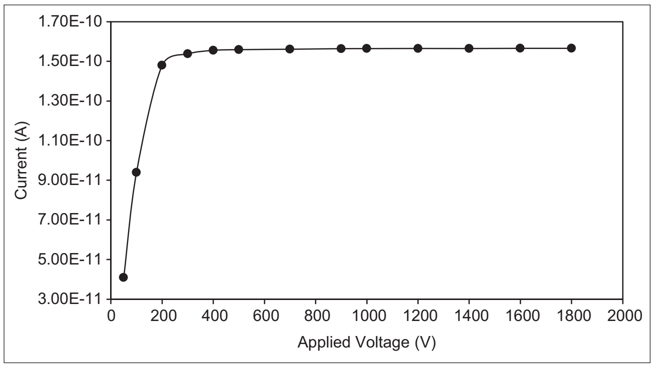

Figure 2: Ionization saturation curve of the DFAIC

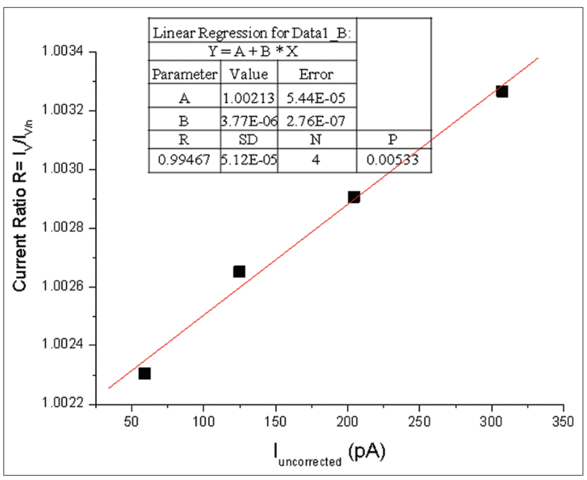

Figure 3: Ion recombination linear fit curve

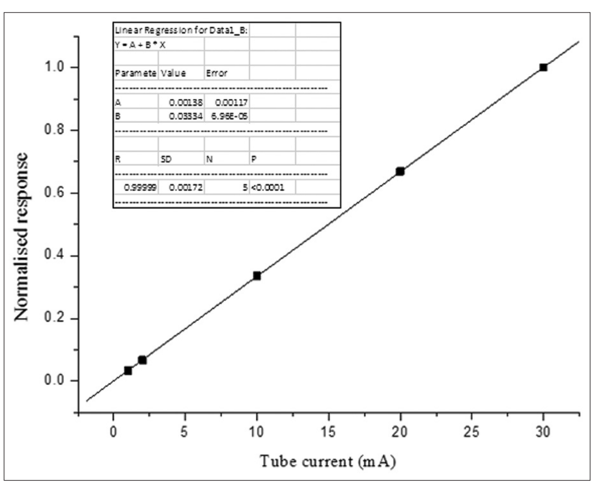

Figure 4: Linearity of response with the variation in tube current of X-ray tube

Internal comparison of DFAIC with the MFAIC was conducted as a preliminary verification of the metrology characteristics of the DFAIC. Table 4 shows the air kerma rate values of RQR beam qualities measured using both the FAICs. The deviation between the two chambers is within the uncertainty of measurement of each chamber.

RQA, RQT, and RQRM beam qualities generated were standardized using DFAIC, and Table 5 gives the air kerma

Table 4: Air kerma rate measurements for radiation qualities in radiation beam qualities using diagnostic range free-air ionization chamber

Beam quality (kV)	Air kerma rate at 1 m (Gy/h)		Ratio
	DFAIC	MFAIC	
RQR3 (50)	9.5282E-02	9.5289E-02	1.000
RQR4 (60)	1.3529E-01	1.3525E-01	1.000
RQR5 (70)	1.8319E-01	1.8334E-01	0.999
RQR6 (80)	2.2616E-01	2.2570E-01	1.002
RQR7 (90)	2.7688E-01	2.7430E-01	1.009
RQR8 (100)	3.3511E-01	3.3550E-01	0.999
RQR9 (120)	4.5529E-01	4.5530E-01	1.000
RQR10 (150)	6.4762E-01	6.5165E-01	0.994

DFAIC: Diagnostic range free-air ionization chamber, MFAIC: Medium energy primary standard free-air ionization chamber, RQR: Radiation qualities in radiation

Table 5: Air kerma rate measurements of the radiation qualities based on aluminum added filter, radiation qualities based on copper added filter, and radiation qualities in radiation beams for mammography beam qualities using diagnostic range free-air ionization chamber

Beam quality (kV)	Added filtration to RQR (mm)	HVL (mm) Al	Air kerma rate at 1 m (Gy/h)
RQA2 (40)	3.96 Al	2.19	9.5041E-03
RQA3 (50)	9.83 Al	3.80	6.4061E-03
RQA4 (60)	15.89 Al	5.39	5.8940E-03
RQA5 (70)	22.8 Al	6.77	7.3613E-03
RQA6 (80)	25.5 Al	8.40	8.1203E-03
RQA7 (90)	33.5 Al	9.68	9.5927E-03
RQT8 (100)	0.215 Cu	7.06	1.4281E-01
RQT9 (120)	0.258 Cu	8.80	2.0104E-01
RQRM2 (28)	0.3 Al	0.33	1.6911E-01

RQR: Radiation qualities in radiation, RQA: Radiation qualities based on aluminum added filter, HVL: Half-value layer, RQT: Radiation qualities based on copper added filter, RQRM: RQR-beams for mammography

Table 6: Uncertainties associated with the diagnostic range free-air ionization chamber for the air kerma measurements of diagnostic beam qualities

Source of component	Relative standard uncertainty (%)	
	Type A	Type B
Physical constants		
Dry air density		0.01
$W_{air/e}$		0.15
Correction factors		
Ion recombination	0.09	0.05
Air attenuation		0.10
Scatter radiation		0.05
Electron loss		0.10
Volume and charge measurement		
Volume		0.4
Ionization charge	0.07	0.05
Distance		0.10
Temperature, pressure, and humidity		0.04
Quadratic summation	0.11	0.47
Combined relative standard uncertainty	0.48	

rates along with the details of the additional filtration used to generate the beam qualities and the HVL of the beams.

Uncertainty of measurements in the standardization of the diagnostic beam qualities for DFAIC is given in Table 6. The uncertainty for MFAIC measurements is 0.51% at 1 sigma level. Uncertainty in the measurement was evaluated using the document "Evaluation of measurement data- Guide to the expression of uncertainty in measurement (GUM)(JCGM 100:2008)"[24] for DFAIC and the primary standard MFAIC.

Dissemination of standards to the users in the field of diagnostic radiology

The aim of establishing and standardizing diagnostic beam qualities is to provide traceable calibration to the users in the field of diagnostic radiology. Calibration of solid-state detectors/instruments and ionization chambers from different diagnostic radiology facilities have been carried out, and the values compared with the certificate values of the manufacturer which are traceable to primary standard FAICs of international standards laboratories. Calibration was carried out by substitution technique where the detector's reference point is placed at the point where the air kerma rate is measured using the DFAIC. Table 7 gives details of the beam qualities compared, detectors used, and the deviation between the reference values established in the laboratory with the user instrument readout value. The uncertainty in calibrating/testing of the instrument at 95% confidence level (K = 2) is ±3%. Table 7 gives details of the uncertainty of each instrument quoted by the manufacturer traceable to an international standard. For air kerma measurements, compliance with the manufacturer quoted limit of the values is based on ILAC-G8:03/2009.[25] Of the 11 beam qualities tested, two measurements plus its uncertainty were not complying

Table 7: Comparison of the air kerma rate measured with commercially available detector system

Beam quality (kV)	Instrument/detector	Reference HVL (laboratory) (mm Al)	HVL measured user instrument (mm Al)	Air kerma rate (Gy/h) at 1 m	Measured air kerma rate using user instrument (Gy/h) at 1 m	Percentage deviation of user air kerma rate with respect to reference value	UC of instrument/detector at 95% confidence level (k=2), %	Compliance of air kerma with the manufacturer specified limit
RQR3 (50)	PTW NOMEX multimeter	1.90	1.86	0.0953	0.09596	0.69	±2.5%	#
RQR5 (70)	PTW NOMEX multimeter	2.71	2.69	0.1832	0.1820	−0.66	±2.5%	#
RQR7 (90)	PTW NOMEX multimeter	3.63	3.64	0.2756	0.2769	0.47	±2.5%	Compliance (≤ ±3.5%)
RQR10 (150)	PTW NOMEX multimeter	6.76	6.98	0.6483	0.6510	0.42	±2.5%	Compliance (≤ ±3.5%)
RQR2 (40)	RTI Piranha	1.40	1.37	0.0526	0.0527	0.19	±1.7%	Compliance (≤ ±5%)
RQR6 (80)	RTI Piranha	3.16	3.12	0.2262	0.2244	−0.80	±1.7%	Compliance (≤ ±5%)
RQR8 (100)	RTI Piranha + DCT 10	4.11	4.09	0.3351	0.3380	0.87	±2%	Compliance (≤ ±5%)
RQR9 (120)	RTI Piranha	5.16	5.14	0.4553	0.4558	0.11	±1.7%	Compliance (≤ ±5%)
RQT8 (100)	RTI Piranha	7.06	7.11	0.1428	0.1430	0.14	±1.7%	Compliance (≤ ±5%)
RQT9 (120)	RTI Piranha	8.80	8.62	0.2010	0.2001	−0.45	±1.7%	Compliance (≤ ±5%)
RQRM2 (28)	RTI Piranha	0.33	0.35	0.1691	0.1697	0.35	±1.7%	Compliance (≤ ±5%)

#It is not possible to state compliance using a 95% coverage probability for the expanded uncertainty although the measurement result is below the limit (refer to ILAC-G8:03/2009; section 2.3 [c]). RQR: Radiation qualities in radiation, RQT: Radiation qualities based on copper added filter, RQRM: RQR-beams for mammography, HVL: Half-value layer, UC: Uncertainty with the limits quoted by the manufacturer even though its measurements were within the limit.

Conclusion

Diagnostic range free-air ion chamber is designed and developed in the laboratory for 20-150 kV beam standardization. The establishment of diagnostic range air kerma standard and its dissemination to the users in the field of diagnostic radiology is achieved in this work. An air kerma-based calibration facility for the calibration of diagnostic range instruments is established in the country. Characterization of DFAIC and comparison of the chamber with the primary standard MFAIC maintained in the laboratory are done with satisfactory results. Experimental measurements were carried out to determine the various correction factors for DFAIC. Uncertainty associated in air kerma measurements have been evaluated for the DFAIC. The chamber will be used as an absolute standard for air kerma measurements in diagnostic range. The evaluation of correction factors by Monte Carlo technique and participating in international intercomparison will aid in establishing the chamber as a primary standard in the X-ray diagnostic energy range.

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Conflicts of interest

There are no conflicts of interest.

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