Impact of a high-voltage generator replacement on the BIPM standards for K_{air} and D_w in medium-energy x-rays

D T Burns, P Roger, C Kessler

1. Introduction

The BIPM holds a free-air chamber primary standard FAC-M-01 for medium-energy x-rays developed in the early 1970s and maintains a series of four reference beams in the range from 100 kV to 250 kV. The last significant change to the reference beams was the installation of a new x-ray tube and high-voltage generator in 2004 and since that time reference air-kerma measurements using FAC-M-01 have shown the air-kerma rate to be stable at the sub-0.1 % level and air-kerma calibration coefficients N_K for the most stable reference chambers to be reproducible at around the 0.02 % level. Over the past few years a primary standard of absorbed dose to water has been developed, based on the free-air chamber, as described in a report to the CCRI(I) in 2017 (Burns *et al.* 2017).

In 2019 the high-voltage generator started to display an intermittent fault and, given the age of the various system components and its critical use as the international reference, a plan was developed to install a new generator, x-ray tube, automated measurement bench and free-air chamber in parallel with the existing arrangement. As it happens, the existing generator, a Seifert Isovolt 320 HS, failed in early 2020 and in June 2020 it was replaced by a new generator, a GE Isovolt Titan E 320, which will eventually serve the new x-ray facility currently under development.

Meanwhile, the comparison and calibration services continue and the purpose of the present report is to summarize the measurements that were made to ensure that any impact of the new generator is fully taken into account.

2. Measurement of generating voltage and anode current

The new generator was connected using new high-voltage cables to the existing system of measurement of the voltage, based on a pair of 1:10000 voltage dividers (one for the positive generator and one for the negative) designed, constructed and calibrated at the BIPM. The generator was operated by selecting the input parameter V_{send} such that the generating voltage V_{gen} was determined to be exactly as for the existing generator. This voltage is evaluated as $V_{gen} = F_{div} V_{out}$, where F_{div} is the divider calibration factor and V_{out} is the divider voltage output (this expression has been simplified; in reality the bipolar arrangement has two dividers, each with its own value for F_{div}, and V_{gen} is a difference measurement). This does not mean that V_{send} itself has the same value as previously, because the old and new generators do not have the same internal calibration. For information, the values for V_{send} are noted in Table 1.

Table 1. Values for V_{send} required to give the stated generating voltage V_{gen}.

Generating voltage V_{gen}	100 kV	135 kV	180 kV	250 kV
V_{send} previous generator	98.84	133.89	178.97	249.43
V_{send} new generator	98.87	133.67	178.40	248.35
Ratio new/previous	1.0003	0.9984	0.9968	0.9957

It is perhaps relevant that the divider output V_{out} is read as a d.c. voltage using a Keithley 2000 multimeter. The input from the generator, however, uses modern technology that has significant ripple at a frequency determined by the internal low-voltage a.c. source. Furthermore, the old and new generators are not the same in their implementation of this technology (neither the same frequency nor the same ripple). This raises the possibility that the relationship between V_{gen} determined as described above, chosen to be the same for the old and new systems, and the *effective* generating voltage seen by the x-ray tube might depend in a complex way on the electrical characteristics of the old and new assemblies. In other words, arranging to have the same V_{gen} for the new system does not guarantee that the *effective* generating voltage is unchanged.

The anode current I_{anode} is determined by measuring the d.c. voltage across a standard resistor. Because the arrangement is bipolar, this resistor is at a high voltage and so a complex arrangement involving voltage-to-frequency conversion and an optical fibre is used to transmit the reading to the controlling computer. Comparing the old and new arrangements, there was no change at the 0.03 % level in the value for I_{anode} required to obtain the reference air-kerma rate of 0.5 mGy s^{-1} at each radiation quality.

3. Stability of the air-kerma rate

During each day of measurements, the air-kerma rate was determined using the primary standard over a period of approximately 1 hour for each radiation quality, simulating the typical measurement procedure employed during comparisons and calibrations. The mean air-kerma rate was determined to typically 0.01 % at each quality on each day. No systematic drift with time was observed over each 1 hour of measurements. This performance is well inside the functional specification of the new generator of 0.03 % over 1 hour.

Over a period of 6 months the air-kerma rate was shown to have a day-to-day standard deviation of around 0.03 % at each radiation quality, similar to the value obtained with the previous generator.

4. Measurements of half-value layer

The copper half-value layer (HVL) for each of the 100 kV and 250 kV radiation qualities was measured using the same combinations of filters as used for the corresponding measurements made in 2015 with the previous generator. The results are shown in Table 2.

Table 2. HVL expressed in mm of copper.

	100 kV	250 kV
2015 previous generator	0.14727(3)	2.4760(3)
2020 new generator	0.14732(3)	2.4759(3)

It is clear that the results for each quality agree within the statistical standard uncertainty of the measurements, shown in parentheses. Note that the stated uncertainty of 30 nm (for 100 kV) does not imply that the absolute HVL is known to this accuracy, but rather that the reproducibility of the HVL is determined at this level (having used the same filters, the uncertainty of their stated thickness does not enter in this relative determination).

5. Stability of air-kerma calibration coefficients

During the test period, several national reference standards sent to the BIPM for comparison or calibration in terms of air kerma had been calibrated previously using the old generator. The results for four such chambers - from the GUM (Poland), the VNIIM (Russia) and the IAEA - were included in the assessment of stability, as well as those for the BIPM reference Exradin A12 and PTW 30013 chambers.

The results are presented in Table 3 in terms of the calibration coefficient N_K obtained in 2020 relative to that obtained previously. For individual chambers and radiation qualities changes of typically 0.03 % to 0.04 % are observed. However, the mean change for each quality given in the penultimate row of the table is not significant at the level of the standard uncertainty of 0.02 %. It is concluded that there is no significant change to the values for N_K determined at the BIPM resulting from the replacement of the generator.

Table 3. Air-kerma calibration coefficients measured in 2020 relative to those measured previously.

	100 kV	135 kV	180 kV	250 kV
Exradin 12-XA081741	0.9998	1.0001	1.0001	1.0003
PTW 30013-9750	0.9999	1.0005	0.9997	1.0001
NE 2561-301 (GUM)	0.9995	0.9999	1.0000	1.0002
PTW 30010-0526 (VNIIM)	1.0003	0.9997	0.9995	0.9991
NE 2561-265 (IAEA)	0.9997	0.9997	1.0002	1.0004
NE 2611-145 (IAEA)	0.9992	1.0002	1.0005	1.0011
mean	0.99973	1.00002	1.00000	1.00020
standard uncertainty	0.00015	0.00013	0.00015	0.00025

6. Stability of the absorbed-dose standard

For the BIPM absorbed-dose standard for medium-energy x-rays, the situation is more complex. This is because the physical standard remains the free-air chamber and the conversion from air kerma to absorbed dose to water involves measured ratios I_w/I_{air} of the ionization current in water and air for a series of sample chambers. Consequently, the absorbed dose to water is not free to change independently of the air kerma, but in fact their ratio is defined by (Burns *et al.* 2017)

$$\frac{D_{\mathrm{w}}}{K_{\mathrm{air}}} = \frac{I_{\mathrm{w}}}{I_{\mathrm{air}}} \, k_{\mathrm{rn}} \ C_{\mathrm{MC}} \,, \qquad (1)$$

where C_{MC} is a conversion coefficient (for the particular chamber type under measurement) evaluated using Monte Carlo methods and k_{rn} is a measured correction for the radial non-uniformity of the beam at the reference depth of 2 g cm^{-2} in water, for this chamber type. Note that an important consequence of Equation (1) is that the ratio of the calibration coefficients $N_K = K_{air}/I_{air}$ and $N_{D,w} = D_w/I_w$ for a given chamber type is, in principle, fixed according to

$$\frac{N_{D,\mathrm{w}}}{N_K} = k_{\mathrm{rn}} \ C_{\mathrm{MC}} \,. \qquad (2)$$

In practice, however, the ratio D_w/K_{air} is determined using Equation (1) for a series of reference chambers of different types and the best estimate of D_w/K_{air} , denoted as the kerma-to-dose conversion factor $C_{w,air}$, is evaluated from these data along with its standard uncertainty (a detailed uncertainty analysis is presented in Burns *et al.* 2017). Subsequently, for a given user chamber we have $N_K = K_{air}/I_{air}$ and $N_{D,w} = C_{w,air}\, K_{air}/I_w$.

Following the change of generator, new measurements of I_w/I_{air} were made for the BIPM reference PTW 30013 and Exradin A12 chambers, as well as for three other PTW 30013 chambers available for measurement (one kindly on loan from each of the ARPANSA and the NRC) in order to obtain information on the reproducibility of I_w/I_{air} for a given reference chamber type. The results for the PTW 30013 chambers are given in Table 4a and those for the Exradin A12 chamber in Table 4b, along with the corresponding values for C_{MC}, k_{rn} and D_w/K_{air}

Table 4a. Results I_w/I_{air} for the PTW 30013 chamber type.

	100 kV	135 kV	180 kV	250 kV
PTW 30013-9750	1.1326	1.3241	1.3172	1.2290
PTW 30013-9749	1.1304	1.3238	1.3172	1.2287
PTW 30013-7470 (ARPANSA)	1.1322	1.3250	1.3174	1.2289
PTW 30013-1527 (NRC)	1.1330	1.3246	1.3176	1.2290
mean	1.1321	1.3244	1.3173	1.2289
standard deviation	0.10%	0.04%	0.013%	0.012%
C_{MC} (PTW 30013)	1.0405	1.0717	1.0876	1.1064
k_{rn} (PTW 30013)	1.0031	1.0031	1.0029	1.0023
D_w/K_{air} (PTW 30013)	1.1816	1.4237	1.4369	1.3628

Table 4b. Results I_w/I_{air} for the Exradin A12 chamber type.

	100 kV	135 kV	180 kV	250 kV
Exradin A12-XA081741	1.1397	1.3330	1.3241	1.2315
C_{MC} (Exradin A12)	1.0356	1.0667	1.0825	1.1012
k_{rn} (Exradin A12)	1.0035	1.0036	1.0033	1.0026
D_w/K_{air} (Exradin A12)	1.1844	1.4270	1.4380	1.3597

From the results for the four PTW 30013 chambers at the 180 kV and 250 kV radiation qualities, it is evident that the reproducibility of the measurement system and the chamber positioning is better than 0.015 %, and that the chamber-to-chamber variations for these qualities are similarly good. The significantly higher standard deviation of 0.1 % at 100 kV is probably an indication of increased sensitivity to fine details in the construction of each individual chamber, since the generator itself appears to be more stable in operation for the lower generating voltages.

7. Revised kerma-to-dose conversion factor $C_{w,air}$

The best estimate for $C_{w,air}$ obtained from Tables 4a and 4b (the arithmetic mean for the two chamber types) is presented in Table 5 along with the values determined when using the previous generator, as published in Burns *et al.* (2017).

Table 5. Revised values for the kerma-to-dose conversion factor $C_{w,air}$.

	100 kV	135 kV	180 kV	250 kV
$C_{w,air}$ previous generator	1.1840	1.4294	1.4429	1.3673
$C_{w,air}$ new generator	1.1830	1.4254	1.4375	1.3612
Ratio new/previous	0.9992	0.9972	0.9963	0.9955

It is evident that the absorbed dose to water at the reference depth, relative to the air kerma, is progressively lower for the new generator as the generating voltage is increased, the difference reaching over 0.4 % for the 250 kV quality. It is stressed that this does not represent a change in the BIPM absorbed-dose determination, but rather a change in the conversion coefficient $C_{w,air}$ arising from a real change in the absorbed dose (relative to the air kerma) that will also be seen in the ionization current measured for a user chamber in water (relative to that measured in air). The net effect should be no significant change in the calibration coefficient $N_{D,w}$ for a user chamber.

It is postulated that the decrease in the absorbed dose relative to the air kerma arises from a decrease in the *effective* generating voltage, as described in Section 2, although there is no ready way to verify this assertion.

Regarding the uncertainty, the new values for I_w/I_{air} show closer agreement with the corresponding ratio of calculated cavity doses for each chamber type (see Burns *et al.* 2017). It follows that the revision of $C_{w,air}$ due to the replacement of the generator does not increase its stated standard uncertainty of 0.40 %.

8. Conclusion

The installation of the new generator has no effect on the measured copper half-value layer nor on the calibration coefficients N_K and $N_{D,w}$ for user chambers. However, there is a decrease in the absorbed dose to water at the reference depth of 2 g cm^{-2} relative to the air kerma at the same point free in air, this effect rising to over 0.4 % for the 250 kV radiation quality. This demonstrates the danger of using a kerma-to-dose conversion based only on Monte Carlo calculations, which would not have been re-calculated for a change of generator. It also highlights the need to re-determine $C_{w,air}$ whenever any change is made to the system.

References

Burns D T, Kessler C, Roger P 2017 New BIPM absorbed-dose standard for medium-energy x-rays *CCRI(I)*/2017-06