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TEMPORAL DEPENDENCE OF THE RADIATION MONITORING INSTRUMENTS FOR AREA MONITORING USED AT RADIODIAGNOSTIC AND INTERVENTION FACILITIES

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Area monitoring is a fundamental test at radiodiagnostic facilities to maintain an acceptable level of radiation exposure for employees and members of the public. Experimental measurements were taken in an ionising radiation calibration laboratory. Four area monitor instruments were used. Dose and dose rate measurements were measured in integrated and rate operating modes. The results show that precautions are necessary where the area monitor uses exposure times of ≤2 s. When taking measurements in rate mode for times ≤2 s, the area monitors evaluated show a tendency to underestimate dose rate, the inaccuracy was 41 %, and varied between 34 and 45 % for different energies. It is highly recommendable to work in integrated mode, inaccuracy varied from 2 to 35 %. For measurements taken with exposure times of ≥3 s, the average inaccuracy was 15 % and the range was between 2 and 41 %.

INTRODUCTION

Medical exposures, among all the practices that involve ionising radiation, are responsible for the greatest contribution to population exposure[1, 2]. The International Atomic Energy Agency (IAEA)[1] and International Commission on Radiological Protection (ICRP)[3] recommend monitoring areas related to medical exposure in addition to supervising public areas. Area monitoring is hence a fundamental test in quality control programmes at radiodiagnostic facilities to ensure employees and members of the public face radiation exposure at an acceptable level, which must be lower than the legal limit. Exceeding these limits results in legal consequences ranging from warnings to the total closure of the service.

In this regard, the Secondary Standards Dosimetry Laboratory (SSDL) for each country has responsibility for traceability, accuracy and precision of area monitoring measurements. Ensuring that ionisation chambers are properly calibrated and detectors are traceable is fundamental for the implementation of radiological protection monitoring, security and optimisation programmes in radiodiagnostic and intervention services. A detector without these characteristics will affect the security and protection of individuals and hinder the quality of work.

Area monitors or survey meters are used for the real-time monitoring of exposure and hence to estimate the potential risk to which members of the public and employees working in public areas or examination rooms are exposed. Various factors must be considered (range, precision, calibration, energy dependence, rate meter, etc.)[4] in selecting the appropriate ionisation chamber and solid-state detector for area monitoring. The precision of measurements can be greatly improved by properly understanding the detector in use[5]. Moreover, the IAEA recommends that: 'Radiation protection monitoring instruments should be calibrated in terms of dose equivalent quantities. Area dosimeters or dose rate meters should be calibrated in terms of the ambient dose equivalent, $H^*(10)$, or the directional dose equivalent, $H'(0.07)$'[6].

Report no. 35 of the American Association of Physicists in Medicine establishes that an uncertainty of 30 % for measurements taken with survey meters is sufficient to properly evaluate protection[7]. The IAEA's Technical Reports Series no. 457[8] states that for survey meters, where 'the uncertainty in the absolute risk for stochastic effects is high, a required accuracy of 20 % in dosimetry measurements should be sufficient'. In a study by Adjei *et al.*[9] carried out in an SSDL, >50 survey meters evaluated demonstrated that the calibration factor was within 20 % for 91 % of cases. Similar results were obtained by Suliman *et al.*[10], where >90 % of the survey meters evaluated registered a calibration coefficient within 20 %.

With the new knowledge on exposure risk at low doses, the ICRP and IAEA[1, 11] established a new limit for occupational dose at eye-lens level of 20 mSv per year. Moreover, considering the knowledge available with respect to dose rate and half-value layer (HVL) values for each X-ray system in a radiodiagnostic service that has implemented a quality monitoring programme, it is possible to allow for an uncertainty of 20 % or less, if the same area monitor, duly calibrated in an SSDL, is always used. It should be noted that legal requirements exist, which if not complied with may result in the closure of a radiodiagnostic or intervention service. In this regard, it is hence necessary to improve the accuracy and precision of measurements to avoid exceeding an uncertainty level of 20 %.

There is no unified protocol for the calibration procedure of survey meters in SSDLs. The Human Health Report No. 4 of the IAEA[12] shows that exposure times for calibration vary between 5 and 60 s depending on the SSDL. On the other hand, in radiodiagnosis, exposure times for the different procedures vary greatly, from a fraction of a second to minutes. For example, a thorax X ray can be conducted in 0.04 s, a periapical dental X ray takes 0.5 s, a mammography 1 s, a computerised axial tomography to diagnose a pulmonary embolism 2.5 s and an intervention procedure can easily expose a patient to a single projection lasting 30 s.

Ionisation chambers and solid-state detectors are the principal survey meters used in radiodiagnostics to measure occupational and public exposure. The use of Geiger-Miller detectors is not recommendable, as they present a strong energy dependency on low-energy photons and the response time takes a number of seconds when exposure times used in radiodiagnostics may be a fraction of a second[13, 14]. However, there are few studies examining the dependency of the ionisation chamber and of solid-state detectors for the measures taken in rate or integrated mode at low exposure times.

For monitoring the radiodiagnostic and intervention area, the lowest possible time and current (mA) are generally used to prevent possible harm to the X-ray tube during the completion of the test, with the great majority of area monitoring studies using ionisation chambers conducting the test for times <2.5 s and in rate mode[15–17]. This means that the survey meter must be capable of measuring exposures lasting seconds or fractions of seconds.

This paper shows the influence of exposure time on area monitors during dose rate measurement in rate and integrated modes for tensions of 60, 80 and 100 kV used at radiodiagnostic and intervention facilities.

MATERIALS AND METHODS

Experimental measures were taken at Labprosaud laboratory specifically designed for the calibration of instruments used in diagnostic radiology (http://www.labprosaud.ifba.edu.br/). The instruments of Labprosaud are directly traceable to primary (absolute) standards maintained at the national metrology institute of Germany, Physikalisch-Technische Bundesanstalt (PTB) (https://www.ptb.de/cms/en.html), with uncertainty within 3 and a 95 % confidence interval. A General Electric ISOVOLT TITAN E X-ray system with ISOVOLT 160 M2 tube, with output voltage range from 5 to 160 kV, output current range from 0.2 to 10 mA and high frequency was used. The radiation qualities required and the calibration arrangement comply with the requirements of reference standards ISO 4037-1, 2 and 3(https://www.iso.org/obp/ui/#search). The specified reference radiations for the narrow spectrum series dedicated to radiation protection, N60, N80 and N100, were used (Table 1).

The study assessed four radiation measurement instruments, composed of three ionisation chambers (PTW reference chamber, Radcal and Fluke area monitor and survey meter, respectively) and a solid-state detector (Atomtex survey meter). Table 2 provides certain technical characteristics of these systems, taken from the manufacturer manuals.

To PTW system, an electrometer UNIDOS webline, model T10021 and Radcal system an electrometer model 9010 were used, respectively. The meters are identified by letters Atomtex (A), Fluke (F), PTW (P) and Radcal (R). Meters A, F and R are calibrated in an SSDL. They were positioned at 200 cm from the focal spot of the X-ray system and using reference points and orientations as specified by the manufacturer.

The PTW ionisation chamber is directly traceable to primary (absolute) standards (PTB). The total traceable uncertainties for the PTW ionisation chamber were 6 and 4 % for rate and integrated mode, respectively (at a 95 % confidence interval). Hence, calculations of the

Table 1. Characteristics: reference radiations of narrow spectrum series.

Radiation qualities	*E* (keV)	Tube potential kV	Additional filtration (mm)	First HVL (mm)	Second HVL (mm)
N60	48	60	0.6 Cu	0.24 Cu	0.26 Cu
N80	65	80	2.0 Cu	0.58 Cu	0.62 Cu
N100	83	100	5.0 Cu	1.11 Cu	1.17 Cu

Table 2. Technical characteristics of ionisation chambers and solid-state detector.

ID	Manufacturer	Model	Type of detector	Magnitude	Dose range	Rate dose range	Energy dependence range	Response time ms
A	Atomtex (http://www.atomtex.com/en/products/portable-dosimeters/at1121-at1123-x-ray-and-gamma-radiation-dosimeters)	AT 1123	Solid state	H*(10)	10 nSv–10 Sv	50 nSv h^{-1}–10 Sv h^{-1}	15 keV–10 MeV	10
F	Fluke Biomedical (http://www.flukebiomedical.com/biomedical/usen/radiation-safety/survey-meters/451p-pressurized-ion-chamber-radiation-detector-survey-meter.htm?pid=54793)	451 P	Ionisation chamber	X, E	No information	0–5 R h^{-1}	20 keV–2 MeV	1800
P	PTW (http://www.ptw.de/1_liter_spherical_chamber.html)	32002	Ionisation chamber	kerma, H*(10)	50.0 nGy–550.0 μGy	18 μGy h^{-1}–90.0 Gy h^{-1}	25 keV–50 MeV	37
R	Radcal (http://www.radcal.com/10×5-180-detail)	9010X5-180	Ionisation chamber	kerma, X	0.1 nGy–20 Gy	1 μGy h^{-1}–15 Gy h^{-1}	30 keV–1.33 MeV	No information

inaccuracy of measurements were taken as against the values obtained for the PTW chamber.

All measurements recorded for the PTW and Radcal meters were corrected for pressure and temperature. The measurements were taken at the normal working rate for each meter and corrected for ambient dose equivalent H*(10), which is used as an estimate of ambient dose equivalent at 10-mm depth[6]. The correction factors to H*(10) are 1.59, 1.73 and 1.71 for N60, N80 and N100, respectively, in accordance with ISO regulation 4037-3 (http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=23727).

The measurements of the dose (D) and dose rate (DRm) were measured in integrated and rate modes, respectively. For each detector evaluated, five measurements were taken at each exposure time of 1, 2, 3 and 5 s, respectively, with 0.7 mA for N60, N80 and N100 radiation quality (Table 1).

The calculated dose rate values (DRc) were calculated using the quotient between dose (D) measured in integrated mode divided by experiment time. Experiment time was measured by PTW equipment (NOMEX, T11049) directly traceable to primary (absolute) standards maintained at the Physikalisch-Technische Bundesanstalt, with uncertainty within 2.8 % with a 95 % confidence interval. The values of experiment time were 1.145 ± 0.024, 2.143 ± 0.026, 3.146 ± 0.019 and 4.953 ± 0.026 s for nominal times of 1, 2, 3 and 5 s, respectively.

The coefficient of determination R^2 for linear correlations was calculated using the dose measurement values in dose mode. Furthermore, the non-linearity of a dosemeter was measured by the ratio $(L_{max} - L_{min}) / (L_{max} + L_{min})$, which should be <0.02[18], where Value L is the maximum or minimum dosemeter response.

RESULTS AND DISCUSSION

To give higher readability of the manuscript, Table 3 shows the percentage of the inaccuracy of measurements for the Atomtex, Fluke and Radcal area monitors taken as against the true values obtained for the PTW system in integrated and rate mode, time exposure and tensions of 60, 80 and 100 kV.

Rate mode measurements

Figure 1 shows the average dose rate (DRm) and standard deviation (SD) values measured in rate mode for different area monitors and at different exposure times with a tension of 60 kV used in diagnostic radiology. The area monitoring meters are identified by letters Atomtex (A), Fluke (F), PTW (P) and Radcal (R).

Figure 1 shows that as exposure time increases, the accuracy of measured dose rate in rate mode becomes closer to the true (absolute) value measured by the PTW chamber. The greatest percentage of inaccuracy

Table 3. The percentage of inaccuracy to Atomtex (A), Fluke (F) and Radcal (R) with respect to the true (PTW) values in integrated and rate mode for different area monitors, time exposure and tension.

	Time	60 kV		80 kV		100 kV	
	s	Integrated mode %	Rate mode %	Integrated mode %	Rate mode %	Integrated mode %	Rate mode %
A	1	101	46	12	46	1	55
	2	116	25	10	22	3	34
	3	64	8	12	8	2	11
	5	17	1	25	5	2	13
F	1	16	49	12	54	16	61
	2	26	42	14	34	0	24
	3	24	35	21	30	6	17
	5	24	28	16	23	4	18
R	1	13	NR	9	NR	47	NR
	2	4	NR	8	NR	23	NR
	3	2	13	3	15	18	8
	5	3	8	4	13	19	12

NR, no record.

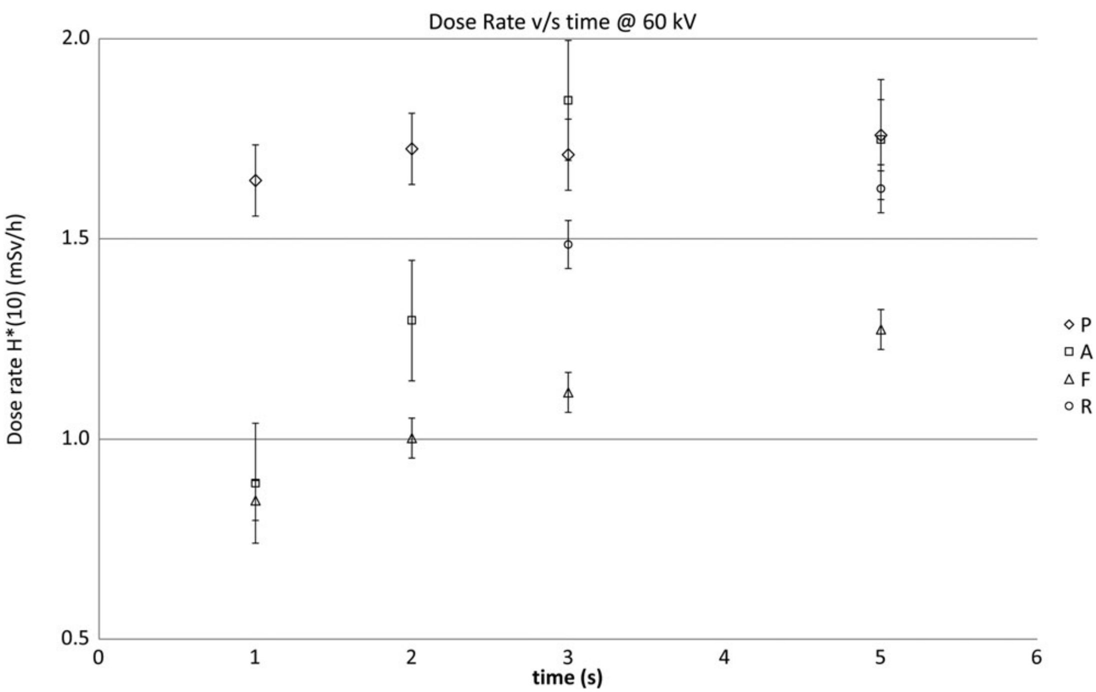

Figure 1. Average dose rate (DRm) and SD values measured in dose rate mode for different area monitoring meters Atomtex (A), Fluke (F), PTW (P) and Radcal (R) and at different exposure times at 60 kV.

was 39 % for the Fluke chamber at 1 s with respect to the PTW chamber, whereas the lowest percentage difference was 1 % for the Atomtex chamber at 5 s with respect to the PTW chamber.

The ranges of inaccuracy for the dose rates measured by the area monitors with respect to the absolute value (PTW) for times ≤2 and ≥3 s were from 25 to 49 % and from 1 to 35 %, respectively. The Radcal chamber was not able to measure the dose rate for times ≤2 s (Table 3).

The average values of the percentage difference between the dose rate and the true (absolute) value were 20, 38 and 10 % for the Atomtex, Fluke and Radcal detectors, respectively.

The PTW ionisation chamber is normally used as a reference chamber for SSDLs. For 60 kV, the greatest percentage difference between the PTW ionisation chamber readings was 6 % for 1 and 5 s. The percentage differences in dose rate for the Atomtex detector and the Fluke ionisation chamber were 49 and 26 % and 33 and 21 % for the times of 1 and 2 s compared with the 5-s readings for each meter, respectively. The percentage differences for dose rate between 3 and 5 s for each area monitor were 6, 12 and 9 % for the Atomtex, Fluke and Radcal monitors, respectively.

Figure 2 shows the average dose rate (DRm) and SD values measured in dose rate mode for different area monitors and at different exposure times with a tension of 80 kV as used in diagnostic radiology. The area monitor meters are identified by letters Atomtex (A), Fluke (F), PTW (P) and Radcal (R).

Figure 2 shows the measurements taken for 80 kV. When exposure time was increased, the dose rate measurements became closer to the true value obtained with the PTW ionisation chamber. The highest dose rate inaccuracy was 54 % for the Fluke chamber at 1 s with respect to the PTW chamber, and the lowest inaccuracy was 5 % for the Atomtex chamber at 5 s with respect to the PTW chamber.

The ranges of dose rate inaccuracy for the area monitors with respect to the true value (PTW) for times ≤ 2 and ≥ 3 s were from 22 to 54 % and from 8 to 30 %, respectively. The Radcal chamber was not able to measure dose rate for times ≤ 2 s at 80 kV (Table 3).

The average values for dose rate inaccuracy with respect to the true value were 20, 35 and 14 % for the Atomtex, Fluke and Radcal detectors, respectively.

At 80 kV, the greatest percentage difference between the readings for the PTW ionisation chamber was 7 % between 2 and 5 s. The greatest percentage differences for dose rate for the Atomtex detector and the Fluke ionisation chamber were 50 and 42 % between 1 and 5 s, respectively. The percentage differences for each area monitor for the dose rate between 3 and 5 s were 13, 10 and 3 % for the Atomtex, Fluke and Radcal monitors, respectively.

Figure 3 shows the average dose rate (DRm) and SD values measured in dose rate mode for different area monitors and at different exposure times with a 100-kV tension used in diagnostic radiology.

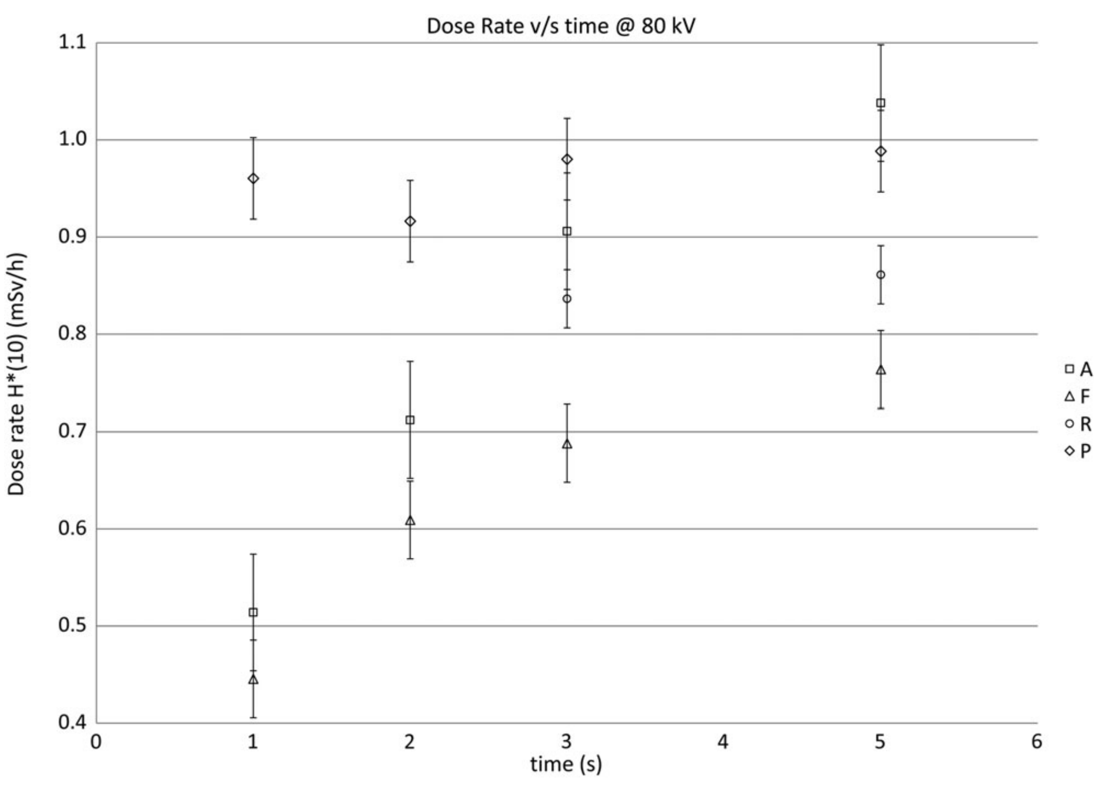

Figure 2. Average dose rate (DRm) and SD values measured in dose rate mode for different area monitor meters Atomtex (A), Fluke (F), PTW (P) and Radcal (R) at different exposure times and at 80 kV.

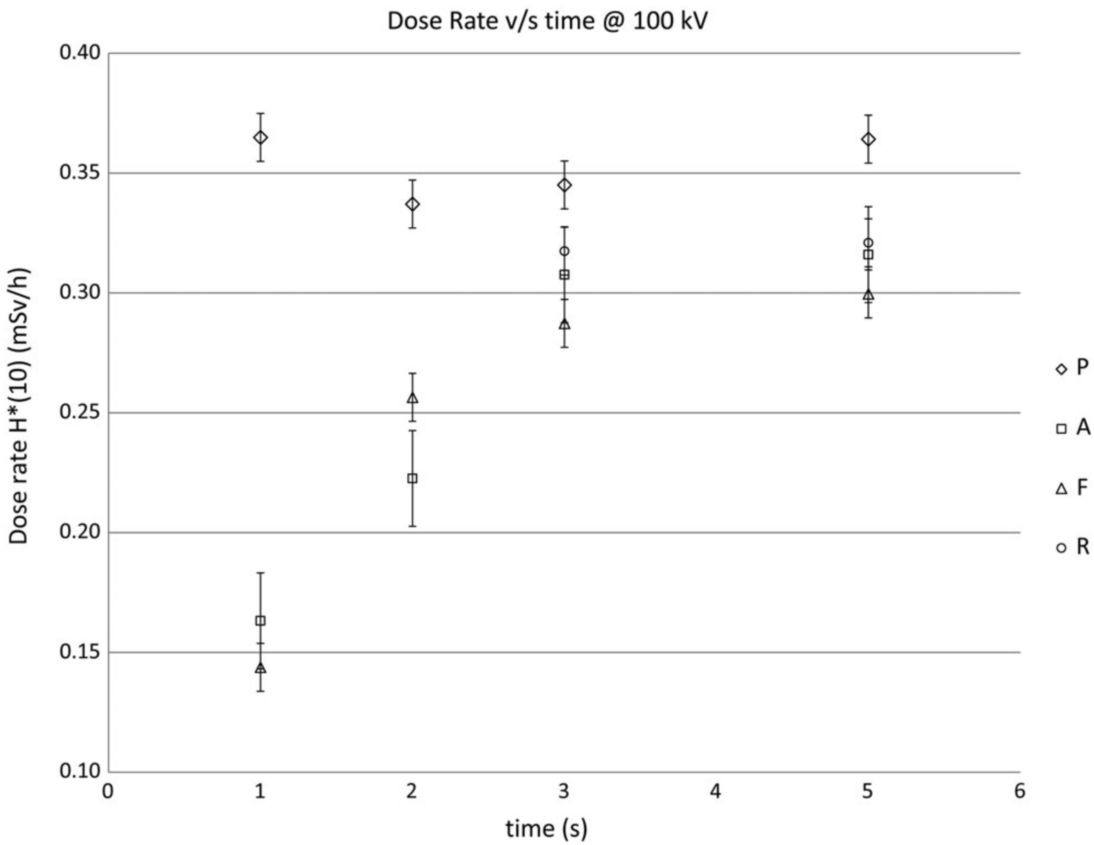

Figure 3. Average dose rate (DRm) and SD values measured in dose rate mode for different area monitor meters Atomtex (A), Fluke (F), PTW (P) and Radcal (R) and at different exposure times at 100 kV.

Figure 3 shows the measurements taken at 100 kV. The same behaviour occurs in that, as exposure time for dose rate measurements increases, the value becomes closer to the true value with respect to the PTW ionisation chamber. The greatest dose rate inaccuracy was 61 % for the Fluke chamber at 1 s with respect to the PTW chamber, whereas the lowest inaccuracy was 8 % for the Radcal chamber at 3 s with respect to the PTW chamber.

The dose rate inaccuracy ranges for the area monitors with respect to the true value (PTW) for times ≤ 2 and ≥ 3 s were from 24 to 61 % and from 8 to 18 %, respectively. The Radcal chamber was not able to measure the dose rate for times ≤ 2 s at 100 kV (Table 3).

The average values for dose rate inaccuracy with respect to the true value were 28, 30 and 10 % for the Atomtex, Fluke and Radcal detectors, respectively.

At 100 kV, the greatest percentage difference between the readings for the PTW ionisation chamber was 7 % between 2 and 5 s. The greatest percentage differences for dose rate for the Atomtex detector and the Fluke ionisation chamber were 48 and 52 % between 1 and 5 s for each meter, respectively. The percentage differences in dose rate between 3 and 5 s for each area monitor were 3, 4 and 1 % for the Atomtex, Fluke and Radcal monitors, respectively.

Integrated mode measurements

Figure 4 shows the average dose rate (DRc) and SD values calculated in integrated mode for different area monitors and at different exposure times with a tension of 60 kV used in diagnostic radiology. The area monitor meters are identified by letters Atomtex (Acal), Fluke (Fcal), PTW (Pcal) and Radcal (Rcal).

Figure 4 shows the measurements taken at 60 kV using integrated mode. The dispersion of dose rate values is lower than the dispersion of values obtained for Figure 1, since varying the exposure time resulted in a maximum DRc inaccuracy of 26 % with respect to the absolute value, except for the Atomtex chamber, which had a maximum inaccuracy of 116 %.

The increased DRc inaccuracy obtained with the Atomtex detector may be due to a non-linearity of 25 %,

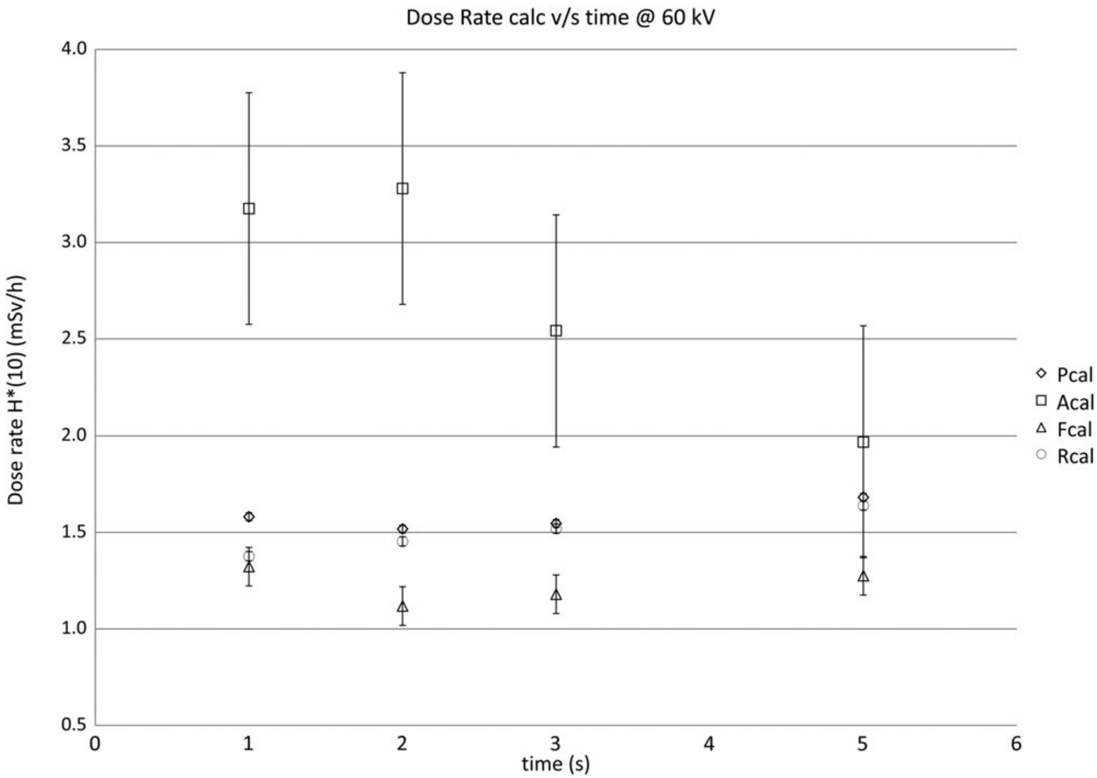

Figure 4. Mean dose rate (DRc) and SD values calculated in integrated mode for different area monitor meters Atomtex (Acal), Fluke (Fcal), PTW (Pcal) and Radcal (Rcal) at different exposure times and at 60 kV.

associated with a coefficient of determination of $R^2 = 0.8721$, and a lack of detector precision because of beam quality at 60 kV, meaning the range of standard deviation varied from 11 to 35 %.

The greatest inaccuracy was 116 % for the Atomtex chamber at 2 s with respect to the PTW chamber, whereas the lowest inaccuracy was 2 % for the Radcal chamber at 3 s with respect to the PTW chamber.

The inaccuracy ranges for the area monitors with respect to the true (PTW) value for times ≤2 and ≥3 s were from 4 to 116 % and from 2 to 64 %, respectively. On taking integrated mode measurements, the Radcal chamber was able to measure the dose for all exposure times used (Table 3).

The average dose rate inaccuracy values for measurements in integrated mode with respect to the true value were 75, 23 and 5 % for the Atomtex, Fluke and Radcal detectors, respectively.

For calibration of the survey meters and area monitors, a deviation of 20 % in measurement accuracy is tolerable[8–10]. In this regard, for measurements at 80 kV in integrated mode, 50 % of the measurements showed >20 % inaccuracy, whereas for measurements at 80 kV in rate mode (Figure 2), 60 % of measurements showed more than 20 % inaccuracy.

The greatest percentage difference between the readings for the PTW ionisation chamber was 10 % between 2 and 5 s. The respective percentage differences for dose rate for the Atomtex detector and the Fluke and Radcal ionisation chambers were 61 and 67 %, 4 and 12 % and 16 and 11 % for times of 1 and 2 s in comparison with the 5-s readings. The percentage differences in dose rate for each area monitor between 3 and 5 s were 29, 8 and 7 % for the Atomtex, Fluke and Radcal monitors, respectively.

Figure 5 shows the average dose rate (DRc) and SD values calculated in integrated mode for different area monitors and at different exposure times with a tension of 80 kV used in diagnostic radiology. The area monitor meters are identified by letters Atomtex (Acal), Fluke (Fcal), PTW (Pcal) and Radcal (Rcal).

Figure 5 shows the dose rate measurements taken at 80 kV using integrated mode. The dispersion of dose rate values is lower than the dispersion of values obtained at Figure 2. The ranges of inaccuracy between the dose rate measurements with respect to the true (absolute) value were from 3 to 25 % for integrated mode (Figure 5) and from 1 to 49 % for rate mode (Figure 2).

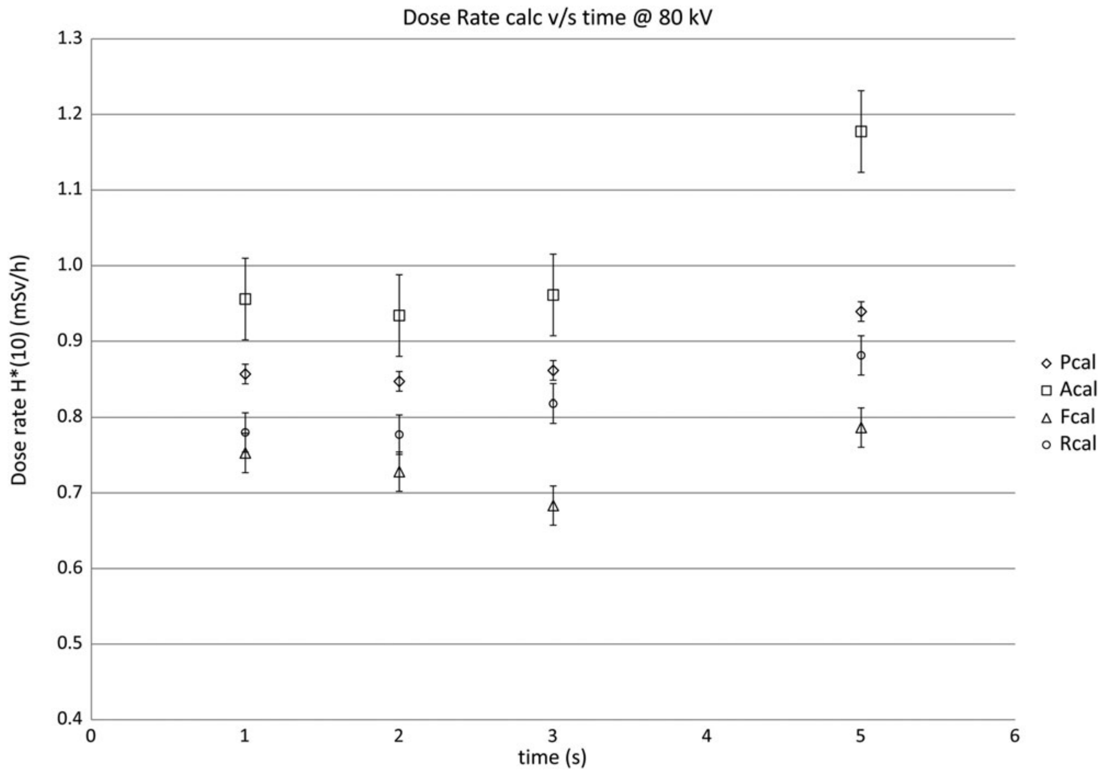

Figure 5. Mean dose rate (DRc) and SD values calculated in integrated mode for different area monitor meters Atomtex (Acal), Fluke (Fcal), PTW (Pcal) and Radcal (Rcal) at different exposure times and at 80 kV.

The greatest inaccuracy was 25 % for the Atomtex chamber for 5 s with respect to the PTW chamber and the lowest inaccuracy was 3 % for the Radcal chamber for 3 s with respect to the PTW chamber.

The inaccuracy ranges of the area monitors with respect to the true (PTW) value for times ≤2 and ≥3 s were from 8 to 14 % and from 3 to 25 %, respectively. On taking integrated mode measurements at 80 kV, the Radcal chamber was able to measure the dose for all exposure times used (Table 3).

The average values for dose rate inaccuracy measured in integrated mode with respect to the true value were 15, 16 and 6 % for the Atomtex, Fluke and Radcal detectors, respectively.

All measurements in Figure 5 have a deviation of <25 % with respect to the true (PTW) dose rate value. From the perspective of radiological protection, a deviation of 20 % in measurement accuracy is tolerable[8–10]. For integrated mode measurements at 80 kV, 17 % of measurements had a deviation in accuracy of >20 %, whereas for rate mode measurements at 80 kV (Figure 2), 60 % of measurements had a deviation in accuracy of >20 %.

The greatest percentage difference between the readings for the PTW ionisation chamber was 10 % between 2 and 5 s. The percentage differences in dose rates for the Atomtex detector and the Fluke and Radcal ionisation chambers were 19 and 21 %, 4 and 7 % and 11 and 12 % for times of 1 and 2 s in comparison with the 5-s readings for each meter, respectively. The percentage differences in dose rate between 3 and 5s were 18, 13 and 7 % for the Atomtex, Fluke and Radcal monitors, respectively.

Figure 6 shows the average dose rate (DRc) and SD values calculated in integrated mode for different area monitors and at different exposure times with a tension of 100 kV used in diagnostic radiology. The area monitor meters are identified by letters Atomtex (Acal), Fluke (Fcal), PTW (Pcal) and Radcal (Rcal).

Figure 6 shows the measurements taken at 100 kV using integrated mode. On varying exposure time, the measurements showed a maximum inaccuracy of 47 % with respect to the true (PTW) dose rate value.

It may be observed in Figure 6 that the values are less dispersed in comparison with Figure 3. The inaccuracy ranges for the dose rate measurements were from 1 to 47 % for integrated mode (Figure 6) and from 8 to 61 % for rate mode (Figure 3).

The greatest inaccuracy was 47 % for the Rcal chamber at 1 s with respect to the Pcal chamber, and

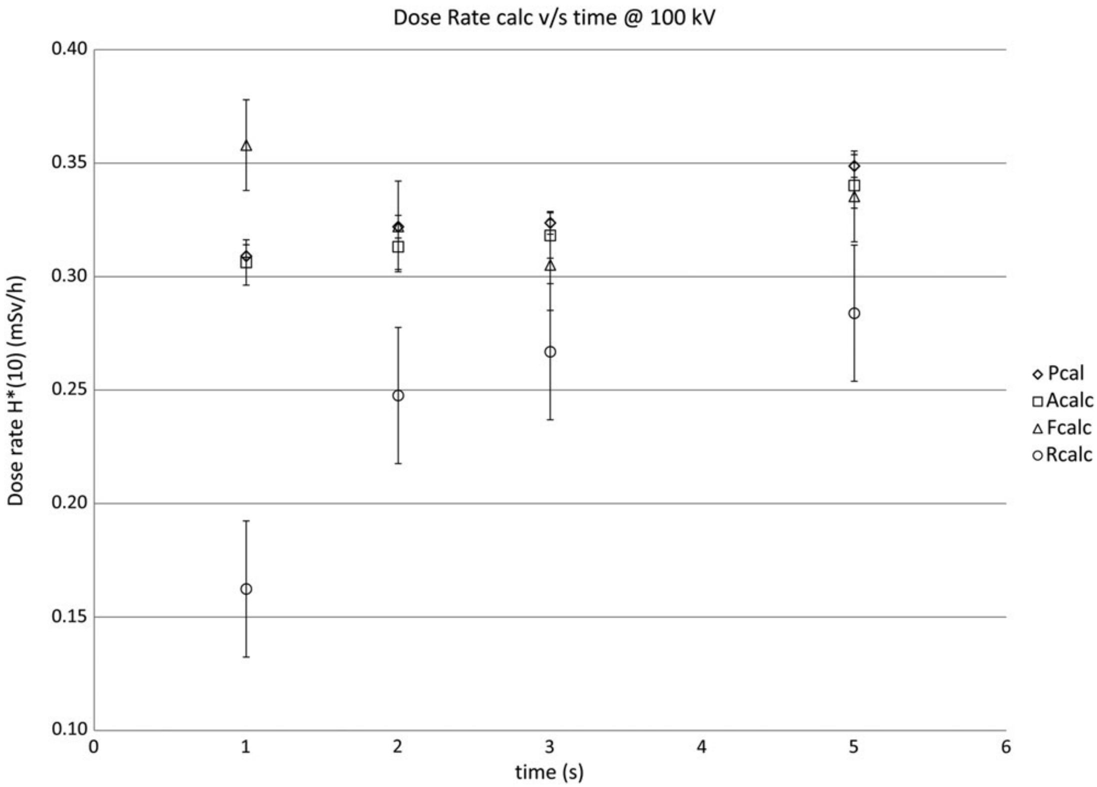

Figure 6. Mean dose rate (DRc) and SD values calculated in integrated mode for different area monitor meters Atomtex (Acal), Fluke (Fcal), PTW (Pcal) and Radcal (Rcal) at different exposure times and at 100 kV.

the lowest inaccuracy was 0.04 % for the Fcal chamber at 2 s with respect to the Pcal chamber.

The inaccuracy ranges for the area monitors with respect to the true (PTW) value for times ≤2 and ≥3 s were from 0.04 to 47 % and from 2 to 19 %, respectively. On taking integrated mode measurements, the Radcal chamber was able to measure the dose rate for all exposure times used. The average dose rate inaccuracies for integrated mode measurements at 100 kV were 2, 6 and 27 % for the Atomtex, Fluke and Radcal detectors, respectively (Table 3).

From the perspective of radiological protection, a deviation in measurement accuracy of 20 % is tolerable[8–10]. In the case of integrated mode measurements at 100 kV, 17 % of measurements had a deviation in accuracy of >20 %, whereas dose rate measurements at 80 kV (Figure 2) showed 40 % of measurements with a deviation in accuracy of >20 %.

The greatest percentage difference between readings for the PTW ionisation chamber was 11 % between 1 and 5 s. The respective percentage differences in dose rate for the Atomtex detector and the Fluke and Radcal chambers were 10 and 8 %, 7 and 4 % and 43 and 13 % for times of 1 and 2 s in comparison with the 5-s readings. The percentage differences in dose rate between 3 and 5 s were 6, 9 and 6 % for the Atomtex, Fluke and Radcal monitors, respectively.

In general, the radiation monitoring instruments evaluated in this study show a tendency to underestimate dose rate when measurements are taken in rate mode for times ≤2 s. The deviation in accuracy varied between 34 and 45 % for the different energies and area monitors evaluated. The Radcal ionisation chamber was even unable to register radiation (Figures 1–3).

On taking integrated mode measurements, the dispersion of dose rate values is lower than that for the values obtained in rate mode. Moreover, in integrated mode, it was possible to calculate dose rate for all exposure times and different radiation beam qualities. The average deviations in accuracy in integrated mode for exposure times of ≤2 s were 7, 14 and 17 % for the Atomtex (excluding values at 60 kV), Fluke and Radcal monitors, respectively.

The values obtained with the Atomtex detector in integrated mode for 60 kV at 1, 2 and 3 s (Figure 4) and the values obtained with the Radcal chamber in integrated mode for 100 kV at 1 s (Figure 6) suggest that this type of evaluation is necessary to develop knowledge regarding each area monitor and to improve the accuracy and precision of measurements for the different energies and exposure times.

The results of this study show that precautions must be taken if area monitoring is performed with exposure times of $\leq$2 s. It is highly recommendable to work in integrated mode. In this case, inaccuracy varied from 2 to 35 % for the different energies and monitors evaluated, except in the case of the Atomtex detector for 60 kV at 1 and 2 s, where average inaccuracy was 108 %. In light of the foregoing, this type of evaluation is necessary to develop knowledge of each area monitor. It is necessary to take into account exposure time and operation mode in order to optimise the accuracy and precision of area monitors.

For measurements taken with exposure times of $\geq$3 s, the average inaccuracy was 15 % and the range was between 2 and 41 %. The greatest percentage difference between dose rates measured in rate or integrated mode was 37 % for 60 kV, using the Atomtex detector. All the other percentage differences between dose rates measured in rate or integrated mode were $<$12 %.

From the perspective of radiological protection, a variation of 49 %, equivalent to a differential factor of 2 in dose rate measurement, in the monitoring of an area may be significant for the safety of the public or of occupationally exposed staff. For example, a radiodiagnostic service with a workload of $W = 320$ (mAmin/week) with a dose rate of 0.4 mSv h^{-1}, using a technique of 220 mAs for a lateral column procedure results in a weekly dose of 0.01 mSv sem^{-1}. Increasing the dose by a factor of 2 means the result will be a weekly dose of 0.02 mSv sem^{-1}, which is 100 % higher than the recommended limit for an uncontrolled area[19, 20]. These differences may be even greater if one takes into account the new recommendation of the ICRP for eye-lens doses for occupational exposure, which is 20 mSv per year.

The results of this study coincide with the recommendations of the IAEA Handbook[18], which advise that measurements of the monitored area should be taken in integrated mode, and with the recommendation of Report 147 of the NCRP[19], which recommends measuring using exposure times of $>$3 s.

It is evident that knowledge of the characteristics of survey meters for diagnostic radiology measurements is highly important[5]. Considering exposure time and operation mode for an ionisation chamber or solid-state detector is necessary in order to improve the accuracy and precision of measurements and to optimise area monitoring.

CONCLUSIONS

The radiation monitoring instruments evaluated in this study show a tendency to underestimate dose rate when measurements are taken in rate mode for times $\leq$2 s. This type of evaluation is necessary to develop knowledge of each area monitor. It is necessary to take into account the exposure time and operation mode in order to optimise the accuracy and precision of area monitors.

The results of this study show that precautions must be taken if area monitoring is performed with exposure times of $\leq$2 s. It is highly recommendable to work in integrated mode.

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