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CONSIDERATIONS CONCERNING THE USE OF COUNTING ACTIVE PERSONAL DOSEMETERS IN PULSED FIELDS OF IONISING RADIATION

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Active personal electronic dosemeters (APDs) exhibit limitations in pulsed radiation fields[(1)], which cannot be overcome without the use of new detection technology. As an interim solution, this paper proposes a method by which some conventional dosemeters can be operated in a way such that, based on the basic knowledge about the pulsed radiation field, any dosimetric failure of the dosemeter is signalised by the instrument itself. This method is not applicable to all combinations of APD and pulsed radiation field. The necessary requirements for the APD and for the parameters of the pulsed radiation field are given in the paper. Up to now, all such requirements for APDs have not been tested or verified in a type test. The suitability of the method is verified for the use of one APD used in two clinical pulsed fields.

INTRODUCTION

Active personal electronic dosemeters (APDs) have many advantages over passive personal dosemeters and are, therefore, used in addition to or even as a replacement for passive dosemeters. Besides their capability to measure even very small dose increments with good precision, they can generate a warning indication in the case of a high dose or dose rate value so that the wearer of the dosemeter can react and avoid or reduce further dose accumulation.

There is, however, a general limitation with respect to measurements in fields of very high dose rates. This could be of concern in the case of accidental exposure if this is accompanied by high dose rates. Special care is required in pulsed fields, as these always have enhanced dose rates in the pulse as compared with a continuous field leading to the same dose in the same time span.

Nearly all radiation fields in human and animal medicine are pulsed, e.g. in X-ray diagnostics and accelerator-based therapy. For APDs this is a problem, especially for those using pulse-counting techniques, since the dose rate in the pulse may exceed the specified dose rate range of the instrument. Unfortunately, both the amount of influence on the measured value and the method for type testing the performance of APDs in such fields have not yet been established. Initial measurements have been performed in direct radiation fields, e.g. those of thorax diagnostics. The direct exposure simulates an (minor) accident, where a person is irradiated by the direct beam.

Any dosemeter, and thus also the APD, should measure the dose correctly not only in the case of routine measurements but also if an accident or unexpected incident occurs, which may result in higher than expected doses and may even exceed the dose limits. Passive dosemeters are capable of this, but for nearly all currently available APDs, this capability is not given, even for a minor accident[(1)].

This general limitation of APDs cannot be overcome without the use of new detection technology which, however, may result in other restrictions and difficulties and which may not be available in the near future. The benefits of APDs, however, seem so strong that an intermediate solution should be looked for.

The paper presented deals with that topic. It will demonstrate that even electronic dosemeters, which are currently in use, can be operated in such a way that, based on the basic knowledge about the pulsed radiation field, any dose rate overload is signalised by the dosemeter itself. This can be accomplished for some counting APDs by adjusting the dose rate alarm level of the APD to an appropriate level. From a radiation protection point of view, the dose rate alarm is understood as a real-time alert to the user to inform him about an increased dose rate and to allow him to protect himself from further exposure, i.e. change his position, stop his activity or stop the radiation generating apparatus. With respect

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to dosimetry, the identification of an over-range field condition indicates a situation in which the dosemeter cannot measure correctly and will require the immediate measurement of the correct dose with suitable dosemeters, e.g. dosemeters used for diagnostics or therapy or, if possible, by the immediate evaluation of the passive dosemeter worn in parallel.

The prerequisites for applying this method and details of the method to determine the appropriate dose rate alarm level to achieve this will be given in this paper.

TECHNICAL BACKGROUND OF THE MEASUREMENT PROBLEM IN PULSED RADIATION FIELDS

What is a pulsed radiation field for an APD and what is a continuous field? The answer, as given by Ankerhold *et al.*[1], has nothing to do with the properties of the field generator or the physical principles of the detectors. It is based on metrological properties of the commonly used APDs. All APDs integrate the dose rate over a measurement cycle of the order of seconds and all type tests based on national and international standards consider only continuous radiation. The only test point, which has importance for pulsed radiation, is the maximum permitted time to react to sudden dose rate changes, both for the indication and the alarm. The maximum time allowed for APDs is 10 s, for high dose rates only 2 s are allowed[2]. Therefore, definitions suggested are as follows[1]:

A *continuous radiation field* for the application in area and individual dosimetry is an ionising radiation field with a constant dose rate at a given point for periods longer than 10 s, if the power on and off processes are neglected.

A *pulsed radiation field* for the application in area and individual dosimetry is an ionising radiation field which is not a continuous radiation field.

An APD shall be very sensitive to the measurement of small dose values and shall have a very small zero dose reading when not exposed to any additional ionising radiation, i.e. it should measure the natural background dose quite exactly. The natural background radiation is of the order of about 2 μSv per day, thus the APD should be capable of measuring small dose rates of about 1 μSv per day.

In addition, these measurements shall be stable within the rated ranges of the influence quantities, e.g. the temperature. To achieve this, nearly all APDs use pulse-counting techniques, as then the trigger level is a tool to adjust the zero dose properly. The disadvantage of any pulse-counting technique is the dead time, i.e. the time span after the formation of a detector pulse within which the detector cannot detect a further pulse. In continuous fields the performance of APDs is in line with radiation protection requirements; many APDs can measure up to 1 Sv h^{-1}. But this is not sufficient in pulsed fields. These can have high dose rates in the pulse up to about 100 Sv h^{-1}, and even more. Besides the problems due to the pile-up effect, another problem is caused by the fact that the radiation field pulses are much shorter than the measurement cycle of the instrument. Typical radiation pulses in human and animal diagnostics are about 100 ms down to a few milliseconds. If the instrument corrects for dead-time effects, it assumes a constant dose rate during a measurement cycle. As this is not the case for pulsed radiation, the correction is not appropriate.

REQUIRED PRIOR KNOWLEDGE FOR THE WORKAROUND PROPOSED

The proposed method is not universally applicable, it depends on a number of characteristics of both the pulsed radiation field and the APD. The required characteristics and knowledge are listed in the following.

Required knowledge of parameters of the pulsed field

The following parameters of the pulsed radiation field, to which the proposed method shall be applied, must be well known:

(1) T_{pulse}: the minimal length of a radiation pulse in the pulsed radiation field. T_{pulse} is typically in the order of milliseconds (ms).

In the cases where T_{pulse} is shorter than the dead time of the detector circuitry (typically several μs), the exact length of the radiation pulse becomes irrelevant, since in any case, the detector can resolve only one count per radiation pulse.

(2) T_{off}: the time delay between two radiation pulses.

In case of a single shot system, e.g. a diagnostic X-ray system, T_{off} equals the time span between two pulses and can be set to infinity for practical considerations.

(3) f_{repeat}: the minimum repetition frequency of the pulsed radiation field. f_{repeat} is typically in the order of hertz (Hz).

In the case of a single shot system, e.g. a conventional diagnostic X-ray system, f_{repeat} equals the inverse of the time between two exposures and can be set to zero for practical considerations.

(4) $E_{min,field}$ and $E_{max,field}$: the radiation energy of the pulsed radiation field has a spectral distribution. The 10 % percentile at the lower end is given by $E_{min,field}$ and the maximum by $E_{max,field}$.

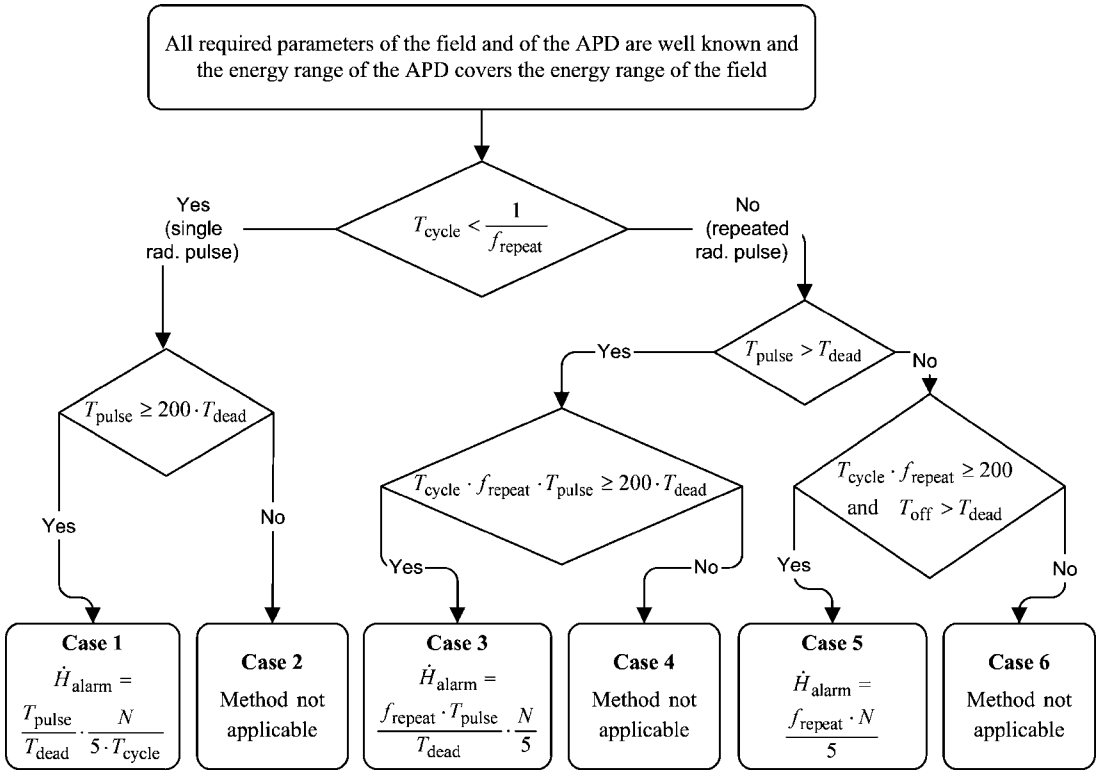

Figure 1. Decision tree for the adjustment of the dose rate alarm level, $\dot{H}_{alarm}$. See text for the meaning of parameters.

The three numerical parameters T_{pulse}, T_{off} and f_{repeat} are inputs to the decision tree as given in Figure 1. The knowledge of the spectral distribution of the field, see (4), is a general requirement for the suitability of the APD and is not specific to pulsed radiation. It is mentioned here because for many pulsed X-ray systems the high voltage is not constant during the pulse. This leads to a lower $E_{min,field}$ value than that expected from the set value of the high voltage and the filtration.

Required knowledge of parameters of the APD

The following parameters of the APD, which shall be used in the pulsed radiation field by applying the proposed method, must be well known:

(a) T_{dead}: the dead time of the detector circuitry used, typically in the order of microseconds (μs).
(b) T_{cycle}: the time span required for a measurement cycle to determine the dose rate value.

The measured dose rate $\dot{H}$ is given as the measured dose accumulated during the measurement cycle divided by the time span of the measurement cycle.

(c) N: the dose per counting pulse of the APD. N is typically in the order of nanosievert (nSv).

In cases where the instrument uses an algorithm to correct the energy dependence of the response of the detector, a range of values are given for N and a value close to the lowest value of N shall be taken for the proposed method.

(d) The energy range of the APD.

At least the minimum energy, $E_{min,APD}$, and the maximum energy, $E_{max,APD}$, as determined in the type test must be well known.

The three numerical parameters T_{dead}, T_{cycle} and N are inputs to the decision tree as given in Figure 1. The requirement (d) is not specific for pulsed radiation. The reason for mentioning it is the same as in the previous paragraph for no. (4).

T_{dead} includes the physical dead time of the detector as well as any additional influence from the electronics and the software. In cases where T_{pulse} is shorter than T_{dead} and T_{off} is larger than T_{dead}, in a first-order approximation, an effective dead time, $T_{dead,eff}$, that equals one-half of the radiation source pulsing period can be used[3]:

$$T_{dead,eff} = \frac{1}{2 \cdot f_{repeat}}. \quad (1)$$

From the fact that T_{off} is assumed to be larger than T_{dead}, the following relation follows:

$$\frac{1}{f_{repeat}} - T_{pulse} > T_{dead}. \quad (2)$$

Additional requirements for the APD

The following additional requirements for the APD, which shall be used in the pulsed radiation field by applying the proposed method, must be fulfilled:

(i) T_{dead} must be non-extendable (non-paralysable).
(ii) The time span T_{cycle} should either be constant or the dependence of T_{cycle} on measurement and field parameters, e.g. H and/or T_{pulse} and f_{repeat}, must be well known. In order to detect even very short durations of the pulsed field it is advisable that T_{cycle} be of the order of 1 s or less.
(iii) The measured dose rate $\dot{H}$ must be calculated and compared with the dose rate alarm level at the end of every measurement cycle and one measurement cycle must be followed by the next without any time gap.
(iv) A transient dose rate alarm must remain activated until it is manually acknowledged.

The requirement (i) assures that even for severe overloads of the APD the measured dose rate value will not fall back to zero. The next requirement (ii) is necessary for the application of the decision tree as given in Figure 1. Requirement (iii) assures that there are no time spans where the dosemeter is inactive and can, therefore, not react to any external dose rate pulse. The last requirement (iv) shall prevent the alarm from not being recognised because, e.g. the dose rate alarm lasts only as long as the transient dose rate exceeds the alarm level, e.g. a few milliseconds (ms).

SETTING OF THE DOSE RATE ALARM

For the method proposed here, a simplified model function of the APD is assumed. The measured dose is assumed as the product of the internal instrument coefficient of the APD, N, and the total number of detector pulses counted.

For APDs with pulse counting techniques the dead-time correction is not working in pulsed radiation fields[1] because any correction assumes a constant dose rate during the time span of the measurement cycle, T_{cycle}, and this is not the case. Therefore, the dead-time loss is not or not fully corrected by the dosemeter. For the purpose of the proposed method it is assumed that the dead-time loss shall not exceed $0.2 = 20\ \%$, to limit the uncertainty to an acceptable value. The dead-time loss is given by the ratio of the total dead time to the measurement time. Neglecting the random distribution of the pulses, a 20 % dead-time loss is equivalent to one detector pulse per every 5 T_{dead}, or a (mean) maximum detector pulse frequency of

$$f_{max} = \frac{1}{5 \cdot T_{dead}}, \quad (3)$$

If the measurement cycle, T_{cycle}, is smaller than the inverse of the radiation pulse repetition frequency $1/f_{repeat}$, then there is only one or no radiation pulse per measurement cycle. Using the above-mentioned simplified model and assuming exactly 20 % dead-time loss, then the related dose H_{max} accumulated during one radiation pulse is given by

$$H_{max} = T_{pulse} \cdot N \cdot f_{max} = T_{pulse} \cdot \frac{N}{5 \cdot T_{dead}}. \quad (4)$$

To convert this dose per pulse to a dose rate value measured by the APD it must be divided by the time span of the measurement cycle, T_{cycle}:

$$\dot{H}_{max} = \frac{T_{pulse}}{T_{dead}} \cdot \frac{N}{5 \cdot T_{cycle}}. \quad (5)$$

For any dose rate value indicated by the APD which is lower than $\dot{H}_{max}$ given by Eq. (5), the dead-time loss is less than 20 % and the dose value measured can be assumed to be correct.

Therefore, the proposed method consists of setting the dose rate alarm level to the dose rate value $\dot{H}_{max}$ as given by Eq. (5):

$$\dot{H}_{alarm} = \frac{T_{pulse}}{T_{dead}} \cdot \frac{N}{5 \cdot T_{cycle}}, \quad (6)$$

see case 1 in Figure 1. If an alarm is indicated, then the dose value is no longer deemed to be correct.

If the measurement cycle, T_{cycle}, is greater than the inverse of the radiation pulse repetition frequency $1/f_{repeat}$, then several radiation pulses are measured per measurement cycle. The mean time over which the detector is exposed during one measurement cycle is then given by $T_{cycle}{:}f_{repeat} \cdot T_{pulse}$, and this product is to replace T_{pulse} in Eqs (4)–(6). This leads to a dose rate alarm level of the following:

$$\dot{H}_{alarm} = \frac{f_{repeat} \cdot T_{pulse}}{T_{dead}} \cdot \frac{N}{5}, \quad (7)$$

see case 3 in Figure 1.

It is interesting to note that in case of radiation pulses smaller than the dead time of the instrument, this formula simplifies to the following:

$$\dot{H}_{\mathrm{alarm}} = f_{\mathrm{repeat}} \cdot \frac{N}{5}, \qquad (8)$$

see case 5 in Figure 1.

Eq. (8) is determined by inserting Eq. (1) into Eq. (7) and considering the limiting case of Eq. (2), i.e. setting $T_{\mathrm{pulse}} = T_{\mathrm{dead}}$ and assuming an equal sign instead of a greater sign in Eq. (2). This leads to $T_{\mathrm{pulse}} \cdot f_{\mathrm{repeat}} = 1/2$ for the limiting case.

It is, therefore, irrelevant for the response of a counting APD in repeated pulsed fields whether the radiation pulse has a length of a femtosecond, picosecond or nanosecond, as long as T_{pulse} is less than T_{dead} and T_{off} is larger than T_{dead}.

The dosimetric meaning of the measured dose rate value is a mean dose rate averaged over the time span of the measuring cycle, T_{cycle}. As T_{cycle} may differ from one dosemeter type to the other, this measured dose rate value may also differ when determined by different dosemeters, especially in the case of a single radiation pulse.

An additional requirement for the applicability of the proposed method is that the probability of the occurrence of false dose rate alarms shall be sufficiently low. It is suggested here that any alarm shall be based on an equivalent of at least 40 counted pulses during the measurement cycle time span. This leads to a statistical coefficient of variation of about $1/\sqrt{40} \approx 16\,\%$, which is in line with the maximum allowed value of 15–20 % as given by IEC 61526[2]. From Eq. (3) the mean time over which the detector must be exposed during one measurement cycle can be determined as $40/f_{\mathrm{max}} = 200 \cdot T_{\mathrm{dead}}$.

In the case of one radiation pulse per measurement cycle this leads to the requirement $T_{\mathrm{pulse}} \geq 200 \cdot T_{\mathrm{dead}}$. In the case of more than one radiation pulse per measurement cycle the requirement $T_{\mathrm{cycle}} \cdot f_{\mathrm{repeat}} \cdot T_{\mathrm{pulse}} \geq 200 \cdot T_{\mathrm{dead}}$ must be fulfilled. If these requirements are not fulfilled, then the method is not applicable, see cases 2, 4 or 6 in Figure 1.

As mentioned above, the suggested alarm setting assures that any dose value measured by the APD without the dose rate alarm occurring is sufficiently correct, provided the data on the pulsed radiation field and the APD are valid. In case a dose rate alarm is activated, then the dose value may still be within acceptable limits, but this is no longer assured. Therefore, the dose value of the incident shall be reassessed by using appropriate equipment. This shall be accomplished by a person having the required expertise.

SUPPORTING MEASUREMENTS

To demonstrate the applicability of the proposed method, measurements were performed at two different X-ray facilities producing pulsed radiation fields using an APD manufactured by Thermo Fisher Scientific (Beenham, UK), of the type 'EPD Mk 2.3'.

Parameters of the APD and the pulsed fields

The first facility was a diagnostic X-ray generator producing only single radiation pulses; the second facility was an angiography X-ray generator with repeated radiation pulses. At the diagnostic X-ray generator, two pulse lengths, T_{pulse}, of 2 and 20 ms were selected and the repetition frequency, f_{repeat}, was less than one pulse per 20 s (0.05 Hz). The high voltage was 70 kV and 125 keV. At the angiography X-ray generator, the pulse length, T_{pulse}, was selected to about 20 ms and three repetition frequencies, f_{repeat}, of 3.125, 6.25 and 12.5 Hz were used. The high voltage was always 85 kV. Any measurement lasted more then 8 s.

The characteristics of the EPD Mk 2.3 are summarised in Table 1. The relative overall standard uncertainty ($k = 1$) of the measurements with the EPD Mk 2.3 is of the order of 20 %, if the original model function of the EPD MK 2.3 for the measurement is used[4]. For the simplified model function used here it will be even larger. The original firmware of the EPD Mk 2.3 uses a measurement cycle, T_{cycle}, of 30 s if the dose rate measured in the prior cycle was low (in the range of a few $\mu\mathrm{Sv\,h^{-1}}$ or less). T_{cycle} is reduced in the ongoing presence of an elevated dose rate. This has to be considered when determining the dose rate alarm value, $\dot{H}_{\mathrm{alarm}}$, especially for the single pulse scenario. The T_{cycle} value of 30 s leads to quite low dose rate alarm values in case of a single pulse shorter than 1 s. To overcome this problem, the firmware of the EPD Mk 2.3 has been modified by the manufacturer, such that T_{cycle} is always set to 1 s, if a dose larger than a selectable dose increment threshold in the range of 0.125–1 μSv is measured within any second. For the described measurements, a value of 0.25 μSv is equivalent to approximately 50 pulses for the EPD Mk 2.3, which is in fair agreement with the proposed minimum count rate of 40 pulses.

The EPD Mk 2.3 uses an algorithm to correct the energy dependence of the response of the detector. This algorithm is not considered by the proposed method. It results in a range for the dose per counting pulse, N, from 4 to 8 nSv. A value of 5 nSv is taken for all further calculations in this paper.

The energy range of the EPD Mk 2.3 covers the energy range of both pulsed radiation fields and all parameters are well known. Therefore, the proposed

Table 1. Relevant parameters of the EPD Mk 2.3.

Parameter	EPD Mk 2.3, value	
	Original firmware, version 11	Modified firmware, version 13 'fast mode setting'
T_{dead}, dead time (μs)	5	5
Dead time non-extendable (non-paralysable)	Yes	Yes
Measurement time span, T_{cycle}	30 s down to 1 s, depending on the dose increment and duration of the pulse	1 s, if >0.25 μSv is measured within any second
Continuous dose rate measurement	Yes	Yes
N, dose per counting pulse (nSv)	5 (4–8)	5 (4–8)

method can be applied to both measurement conditions.

As an example of the calculation of the alarm level for the single pulse at the diagnostic X-ray generator the result for a 2 ms pulse is given by Eq. (9) for the original firmware and by Eq. (10) for the modified firmware, see case 1 in Figure 1:

$$\dot{H}^{\text{original}}_{\text{alarm, diag}} = \frac{T_{\text{pulse}}}{T_{\text{dead}}} \cdot \frac{N}{5 \cdot T_{\text{cycle}}} = 0.013\,\frac{\mu\text{Sv}}{\text{s}} = 48\,\frac{\mu\text{Sv}}{\text{h}} \quad (9)$$

$$\dot{H}^{\text{modified}}_{\text{alarm, diag}} = \frac{T_{\text{pulse}}}{T_{\text{dead}}} \cdot \frac{N}{5 \cdot T_{\text{cycle}}} = 0.4\,\frac{\mu\text{Sv}}{\text{s}} = 1.44\,\frac{\text{mSv}}{\text{h}}. \quad (10)$$

As mentioned, these alarm levels are equivalent to a measured dose rate value averaged over the time span of the measuring cycle, T_{cycle}. The large difference in the values given by Eqs (9) and (10) reflects the difference by the factor 30 between the values of T_{cycle} given by the original and modified firmware.

As an example of the calculation of the alarm level for repeated pulses at the angiography X-ray generator, the result for a repetition frequency of $f_{repeat} = 3.125$ Hz is given by Eq. (11), see case 3 in Figure 1:

$$\dot{H}_{\text{alarm, angio}} = \frac{f_{\text{repeat}} \cdot T_{\text{pulse}}}{t_{\text{dead}}} \cdot \frac{N}{5} = 12.5\,\frac{\mu\text{Sv}}{\text{s}} = 45\,\frac{\text{mSv}}{\text{h}}. \quad (11)$$

$H_{alarm,angio}$ is valid for both versions of the firmware, as the result is independent of T_{cycle}.

Measurements and dosimetry

For the measurements at the diagnostic X-ray generator, two EPD Mk 2.3 were irradiated simultaneously, whereas at the angiography X-ray generator only one EPD Mk 2.3 was irradiated per measurement.

The great variation in the dose rate was only possible for the diagnostic X-ray generator, as the distance between the focal spot of the X-ray tube and the measurement position could be varied between 70 cm and 15 m. For the angiography X-ray generator the distance was constant, only different PMMA and/or lead layers to attenuate the radiation could be used to vary the dose rate. As a reference, a diagnostic dosemeter, type *PID-CF diagnostic dosemeter* with *RQA detector*, manufactured by Scanditronix Wellhöfer GmbH, now IBA Dosimetry, was used. The relative overall standard uncertainty ($k = 1$) of the measurements with this dosemeter is below 10 %. For simplicity, every two or three instruments were irradiated on a metal surface (for the angiography measurements it was the surface of the radiation protection lead rubber apron; for the diagnostic unit it was a metal frame of a table) side by side.

The RQA detector of the diagnostic dosemeter is nearly insensitive to backscattered radiation. The measurement quantity for the RQA detector under these measurement conditions is air kerma free in air, K_a, and the measuring conditions are appropriate for this dosemeter. The EPD Mk 2.3 as individual dosemeter measures the dose quantity $H_p(10)$. In principle, the EPD should be irradiated on an ISO water slab phantom, however, for this special dosemeter the influence of the phantom on the indicated value is negligible.

To compare the measured values of the PID-CF diagnostic dosemeter and the EPD Mk 2.3, it is necessary to convert the K_a values of the PID-CF to the quantity $H_p(10)$. This was done using the values of the quotient $H_p(10)/K_a$ given in the Ankerhold catalogue[5]. For all measurements at the diagnostic

Table 2. Results obtained at the diagnostic X-ray generator, measurement of one single pulse.

Measurement number	Number of measurements	Distance (cm)	H_{ref} (μSv)	H_{EPD} (μSv)	H_{EPD}/H_{ref}	Firmware	$\dot{H}_{alarm}$ (μSv h^{-1})	$\frac{H_{ref}}{H_{alarm}}$	Alarm activated (%)	Pulse length (ms)
1	2	898	0.10	0.0	0.00	Old	48	0.24	0	2
2	2	830	0.12	1.0	8.23	Old	48	0.30	0	2
3	8	1530	3.66	3.9	1.06	New	14 400	0.91	0	20
4	8	1430	4.41	4.3	0.96	New	14 400	1.10	100	20
5	6	1330	5.29	4.8	0.91	New	14 400	1.32	100	20
6	16	630	0.52	0.5	0.96	Old	48	1.30	38	2
7	6	1230	6.43	5.7	0.88	New	14 400	1.61	100	20
8	6	1130	7.89	6.7	0.85	New	14 400	1.97	100	20
9	8	1030	10.5	8.0	0.76	New	14 400	2.62	100	20
10	10	898	1.18	1.1	0.93	Old	48	2.96	80	2
11	10	830	1.35	1.2	0.89	New	1440	3.37	20	2
12	6	930	14.2	10.2	0.71	New	14400	3.56	100	20
13	4	430	1.41	1.0	0.71	Old	48	3.52	100	2
14	6	830	18.6	11.5	0.62	New	14 400	4.65	100	20
15	12	730	1.93	1.3	0.69	New	1440	4.83	33	2
16	8	630	2.76	1.6	0.59	New	1440	6.90	75	2
17	4	530	4.42	2.0	0.45	New	1440	11.1	100	2
18	2	523	4.59	2.0	0.44	Old	48	11.5	100	2
19	6	430	6.75	1.8	0.27	New	1440	16.9	100	2
20	6	330	10.8	2.7	0.25	New	1440	26.9	100	2
21	2	330	116	21.0	0.18	New	14 400	29.1	100	20
22	2	324	12.9	2.5	0.19	Old	48	32.3	100	2
23	4	230	23.9	3.0	0.13	New	1440	59.9	100	2
24	2	230	259	23.5	0.09	New	14400	64.6	100	20
25	2	227	28.7	3.0	0.10	Old	48	71.7	100	2
26	4	180	41.4	2.5	0.06	New	1440	104	100	2
27	2	130	724	7.5	0.01	New	14 400	181	100	20
28	8	130	79.0	1.0	0.01	New	1440	197	75	2
29	2	115	105	0.5	0.00	New	1440	263	100	2
30	18	105	119	0.5	0.00	New	1440	298	0	2
31	4	105	1247	0.3	0.00	New	14 400	312	0	20
32	6	80	207	0.2	0.00	New	1440	518	0	2
33	4	69.5	326	0.0	0.00	Old	48	814	0	2

X-ray generator and those at the angiography X-ray generator, where no or only PMMA absorbers were used, the values given for the RQR series were used. Only for the measurements at the angiography X-ray generator, where lead absorbers were employed, the values given for the RQA series were used.

For most of the different conditions repeated measurements were performed, see column 'Number of measurements' in Table 2. In the case where more than one measurement was performed, the values given are mean values. The value in the column 'alarm activated' gives the percentage of the measurements that lead to an alarm.

Measurement results

The measurement results at the diagnostic X-ray generator were given in Table 2 and those for the angiography X-ray generator, in Table 3. As various field parameters are used, all the parameters are also given in the tables. No influence of the high voltage could be seen, therefore, this value is not given in the table.

As mentioned above, any measured dose rate value is a mean dose rate averaged over the time span of the measuring cycle, T_{cycle}. Therefore, for the single pulse generated by the diagnostic X-ray generator, the dose H_{alarm} of the radiation pulse that should activate the alarm is given by $H_{alarm} = \dot{H}_{alarm} \cdot T_{cycle}$. The quotient of the reference dose, H_{ref}, divided by the dose H_{alarm}—in the following called 'overload ratio'—can be used as a scale to judge the performance of the proposed method and, therefore, all measurements in Table 2 were sorted accordingly. In addition, all the measured values of the EPD Mk 2.3, normalised to the reference dose value, were shown in Figure 2. According to the method presented, the alarm should be activated when this overload ratio exceeds 1.0. It can be seen that for overload ratios larger than about 0.7 the

Table 3. Results obtained at the angiography X-ray generator, measurement of repeated pulses.

Measurement number	Number of measurements	H_{EPD} (μSv)	H_{ref} (μSv)	$\frac{H_{EPD}}{H_{ref}}$	$\overline{\dot{H}_{ref}}$ (mSv h^{-1})	$\dot{H}_{alarm}$ (mSv h^{-1})	$\frac{\overline{\dot{H}_{ref}}}{H_{alarm}}$	Alarm activated within 6 s (%)	Time to alarm (s)	f_{repeat} (1 s^{-1})	Additional attenuation
1	1	94	102	0.92	32	45*	0.70	0		12.5	0.35 mm Pb
2	3	99	95	1.04	26	45	0.57	0		3.125	5 cm PMMA
3	1	133	151	0.88	44	45*	0.97	0		12.5	0.35 mm Pb + 4 cm PMMA
4	2	289	280	1.03	134	180	0.75	0		12.5	4 cm PMMA
5	4	258	247	1.05	67	90	0.75	25	2	6.25	4 cm PMMA
6	4	120	118	1.02	34	45	0.75	100[a]	8	3.125	4 cm PMMA
7	1	70	81	0.87	53	45*	1.19	100	2	12.5	0.35 mm Pb + 3 cm PMMA
8	2	95	102	0.93	41	45	0.92	100	2	3.125	3 cm PMMA
9	2	139	138	1.00	83	90	0.92	100	2	6.25	3 cm PMMA
10	2	330	332	0.99	174	180	0.96	100	2	12.5	3 cm PMMA
11	1	138	125	1.11	57	4*	1.26	100	2	12.5	8 cm PMMA
12	2	404	413	0.98	237	180	1.32	100	2	12.5	2 cm PMMA
13	1	153	140	1.09	71	4*	1.58	100	2	12.5	7 cm PMMA
14	1	231	213	1.08	87	4*	1.93	100	2	12.5	6 cm PMMA
15	1	250	236	1.06	103	4*	2.28	100	2	12.5	5 cm PMMA
16	1	561	687	0.82	426	180	2.37	100	2	12.5	—

[a]Alarm activated after 8 s.
*Dose rate alarm value much too conservative.

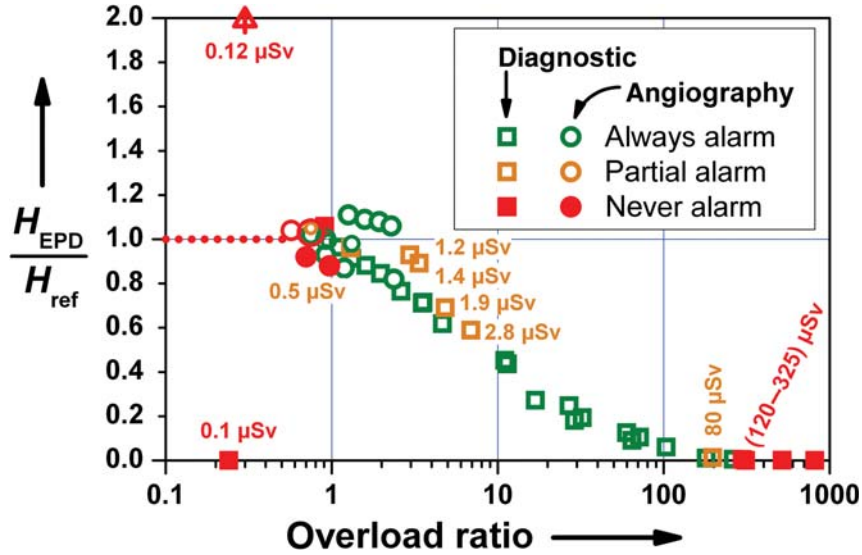

Figure 2. Indication of the EPD Mk 2.3, normalised to the reference dose value, as a function of the overload ratio. For those values where the alarm is only partly activated, the mean dose value indicated by the EPD Mk 2.3 is specified in the figure.

alarm is activated for some measurement conditions, for others it is not. Above 1.0, the alarm is always activated until the overload ratio exceeds a value of about 200, with a few exceptions at measurement conditions where low dose values were measured. Up to a value of the overload ratio of about 2, the EPD Mk 2.3 indicates 80 % or more of the reference value. For an increasing value of the overload ratio the response goes down to a few percent, but still activates the alarm. The alarm is no longer activated when the overload ratio exceeds a value of about 200. This is also shown in Figure 3, where the indication of the EPD Mk 2.3 is shown as a function of the overload ratio. At overload ratios above about 100 the indication of the EPD Mk 2.3 decreases, which should not occur if the dead time were still non-extendable (non-paralysable) even under these extreme over-range conditions. In the case of an ideal non-extendable dead time, the measured values should follow the dotted lines or stay above them. The dotted lines at low overload ratios indicate the expected behaviour. Due to the very low dose values obtained in the experiment for this range of overload ratios in combination with the limited resolution of the indication of the EPD Mk 2.3 of 1 µSv, the measured points do not always follow these lines.

In the case of the angiography X-ray generator the above-mentioned overload ratio must be replaced by the quotient $\dot{H}_{ref}/\dot{H}_{alarm}$, where $\dot{H}_{ref}$ is the mean reference dose rate and should not be mixed with the (peak) dose rate during the radiation pulse. This overload ratio is used again as a scale to judge the performance of the proposed method. Therefore, all measurements in Table 3 were sorted accordingly and the measurement results were also included in Figure 2. It can be seen that for overload ratios larger than about 0.6, the alarm is activated in any case. This is in good agreement with the value of 0.7 for the diagnostic X-ray generator. The time needed to activate the alarm was in most cases about 2 s, only in one case, measurement no. 6, it was about 8 s. In this time span the dose received by the person monitored would be <200 µSv.

As it was not possible to achieve very high dose rates with the angiography X-ray generator; the range of values of the overload ratio is limited to values <2.4. In agreement with the findings for the diagnostic X-ray generator up to this value of the overload ratio, all indicated values of the EPD Mk 2.3 are in sufficient agreement with the reference value. In addition, for these values of the quotient the product of f_{repeat} and T_{pulse} is of the order of 250 ms, i.e. one-fourth of a constant radiation. The EPD Mk 2.3 is capable of measuring at dose rates up to 1 Sv h^{-1} with a maximum deviation of only 2 %[6], the maximum dose rate of about 1.3 Sv h^{-1} (four times $\dot{H}_{ref} = 334$ mSv/h) prevailing during measurement at the angiography X-ray generator, see measurement no. 16 in Table 3, is only a bit higher than this value.

It was also tested, as to whether the method works under conditions where the dose rate alarm value is much too conservative. These measurements are indicated by an asterisk after the value in the $\dot{H}_{alarm}$

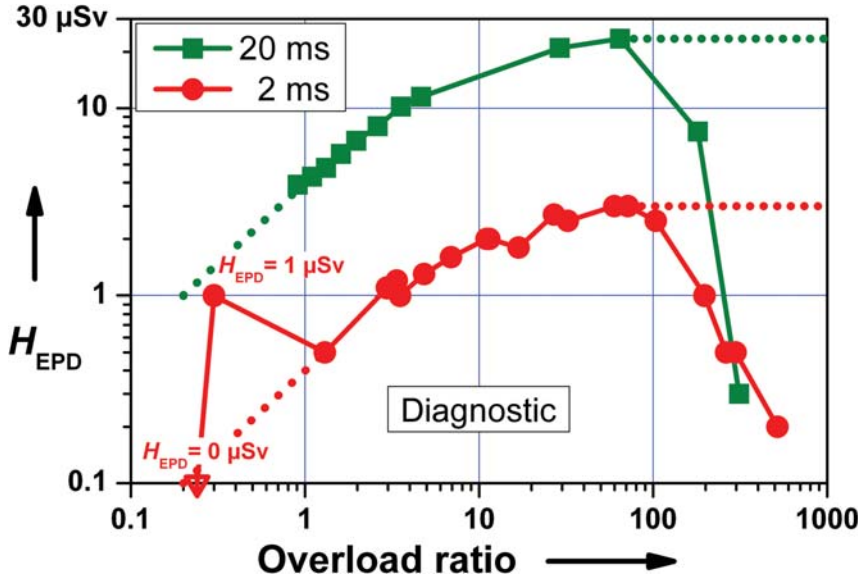

Figure 3. Indication of the EPD Mk 2.3 as a function of the overload ratio.

column. These values are calculated for $f_{repeat} =$ 3.125 Hz, but used in a field of $f_{repeat} = 12.5$ Hz, see measurement numbers 1, 3, 7, 11, 13, 14, 15. The results fit quite well in the data of Table 3 and, as expected, they show no decrease in the indication for overload ratios slightly above unity. This can be seen in Figure 2 by the four green open circles just above the overload ratio of one and above the value of one for the normalised indication.

Discussion of the results

It can be clearly seen that the proposed method provides—under the prerequisite that the instrument complies with the given requirements—a reliable tool to avoid faulty measurements by activating the alarm before the measurement capabilities of the instrument are exceeded. In the case of the single pulse generated by the diagnostic X-ray unit, the method works well for both versions of the firmware that differ by the measuring cycle values, T_{cycle}, of 1 and 30 s.

In the given measurement examples there are large security reserves from the activation of the alarm at a value of 0.6–0.7 for the respective overload ratio to the value of about 2, at which the error of the indication of the APD becomes relevant. This is, at least partly, due to the choice of nearly the lowest value of N within the given range.

There are some cases of values of the overload ratio between 1 and 8, where the percentage value of activated alarms is less than 100 %, but in those cases the reference dose value is <2 µSv and this might explain the missing alarms. In addition, a single dose value of 2 µSv is of no interest to radiation protection, and for a multiple occurrence of the same 'minor accident': firstly, the alarm will occur for at least some of the accidents and secondly, the measured dose is at least 60 % of the reference dose.

It was also shown by irradiations with the angiography X-ray generator that the method works well, even when the assumptions on the pulsed radiation fields are very conservative.

The limitations of the proposed extension of the usage of existing APDs for pulsed radiation fields can be seen in the missing alarm at very high dose rates, i.e. values of the overload ratio higher than about 200. As in these cases the reference dose is quite high, about 0.1 mSv or more, this cannot be due to too low dose values, as assumed above for some cases for a quotient <8. At such dose rates which are more than 2 decades above the nominal dose rate measuring range of the EPD Mk 2.3, the assumption of a non-extendable (non-paralysable) dead time is apparently no longer fulfilled; this is shown in Figure 3. If the method should be applied using the APD of the example, the occurrence of such high values of the overload ratio shall be prohibited by other means.

CONCLUSIONS

A method is proposed to enable the use of existing APDs in some pulsed radiation fields, even if the dosemeter is not capable of measuring in the direct

beam. The key idea of the method is the proper setting of the dose rate alarm of a pulse counting APD, so that as long as the dose rate alarm is not activated, the APD will measure the dose correctly. The value to which the dose rate alarm shall be set depends on the characteristics of both the pulsed radiation field and the APD. In case the dose rate alarm is activated, then the dose value of the incident shall be reassessed by using appropriate equipment. This shall be undertaken by a person having the required expertise.

The required information on the APD must be provided by the manufacturer as it is not available from type test results. The method was proven in two measurement examples using the EPD Mk 2.3 dosemeter in typical pulsed radiation fields common in medicine. The required dose rate alarm level was high enough, so that under normal workplace conditions the alarm would not be activated.

It must be pointed out that the method is not always applicable and the values to which the dose rate alarm is to be set are not universal. The alarm level depends strongly on the properties of the pulsed radiation field and those of the APD. The method will not supersede a type test in pulsed radiation fields. But it will help the practitioner as long as no type test requirements for pulsed radiation fields and (modified) APDs complying with these requirements are available.

In principle, the method is also available to area dosimetry. But it should be used rather to calculate the maximum dose rate that can be measured by an area dosemeter under given conditions of the pulsed field.

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