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Development of measurement methods and dose evaluating algorithms for electronic personal dosimeter

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Abstract: For personal radiation dose monitoring, electronic personal dosimeters (EPD), also known as active personal dosimeter (APD), using silicon diode detector have the advantage capability of measuring and displaying directly the exposure results of gamma, beta and neutron radiations in real time. They are mainly considered as good complement to passive dosimeters to satisfy ALARA principle in the radiation protection. In this paper, the meansurement methods and algorithms for evaluating personal dose equivalents such as Hp(10) and Hp(0.07) from air-kerma are studied and developed in two directions: the first, named energy correction method based on incident energy determined by the ratio of two detector responses with the different filter configurations; the second new method is carried out in the way that matching the shape of a detector's energy response curve to the kerma-to-personal dose equivalent conversion function provides an approximate means of determining the dose equivalent without the need to resolve the actual incident energies. The algorithm has also been experimentally verified at Secondary Standards Dosimetry Laboratory (SSDL) of INST by the beam of radiation defined in ISO 4037-1. The obtained results of personal dose equivalents with errors almost less than 30% in energy range from 20 keV to 1.5 MeV are partially met the EPD design requirements according to the IEC 61526 Standard. The work and results of described in this paper are important basics for design and construction of completed electronic personal dosimeter.

Keywords: *Personal dose equivalent, Silicon diode detector, EPD* .

I. INTRODUCTION

Radiation monitors fall into the categories of environmental radiation monitoring, personal dose monitoring, surface contamination monitoring, radioactive material monitoring and area process monitoring. For personal dose monitoring, electronic personal dosimeter carried in a worker's pocket measures and displays in real time the amount of radiation received while the worker performs their task. This dosimeter is also equipped with a function that issues an alarm in cases where the exposure dosage exceeds a preset value. The development of electronic personal dosimeters has made progress in recent years, and an IEC standard (IEC 61526) has been established for electronic personal dosimeters.

The silicon PIN photodiode detector with its advantage in sensitivity, volume, power consumption, low cost, etc. is one of the key components of the EPD for radiation detection and measurement. However, because the atomic coefficient of the detector is higher than

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that of the tissue material and the sensitive layer is thin, the photon energy response of the Si-PIN detector is not consistent in the energy range from 20 keV to 1.25 MeV, especially in the low-energy region (less than 100 keV), where the photon energy response is high. This characteristic of detector seriously affects the measurement accuracy of the instrument.

The aim of the present study is to develop the measurement methods and algorithms to calculate the dose in terms of two dose quantities Hp(10) and Hp(0.07) (respectively, the personal dose equivalent at 10 and 0.07 mm depth) applicable for photon energies in the range of 20–1250 keV to archive an appropriate photon dosimetry response used for electronic personal dosimeter.

II. METHODS AND ALGORITHMS

Secondary or operational quantities are used for occupational monitoring. The ICRU-39 (1985) has defined the operational quantities for individual monitoring is personal dose equivalent Hp(d). For photons, the reference primary physical quantity is kerma, free in air, or "air kerma", K_a. Like the ambient dose equivalent $H^*(d)$, the personal dose equivalent Hp(d) is not directly measurable and therefore also derived from air-kerma using appropriate conversion coefficient. Energy dependent dose conversion coefficients are used to establish the relationship between the primary physical quantities and the operational quantities Hp(d). So that, for the case of mono-energetic photon at energy E, the personal dose equivalent Hp(d) can be determined by

$$\mathrm{Hp(d)} = \mathrm{C_p(E).K_a(E)} \qquad (1)$$

where $K_a(E)$[Gy] is air-kerma and $C_p(E)$[Sv/Gy] is air-kerma to dose equivalent conversion coefficient. The conversion coefficients from air kerma K_a to the quantities Hp(10) and Hp(0.07) for individual monitoring for workplace monitoring depend on photon energy as shown in Figure 1 (ICRP74 or ICRU51).

A. Energy correction method

The method of correcting the energy response of the Si-PIN detector described here solves the problem arising from over response of the detector in the low energy range. To determine exactly the personal dose equivalent according to Eq.1, the related quantities such as air kerma and dose conversion coefficient must be determined. A simple algorithm for determining personal dose equivalent is showed in fig.2. In the standard laboratory, the air kerma can be obtained by

$$\mathrm{K_a(E) = N\,.\,CF(662keV).\frac{1}{F(E)}} \qquad (2)$$

where N is counts from detector, CF(662) [Gy/Cnt] is calibration factor at 662 keV, F(E) is relative energy response function of detector, which is normalised to photon radiation of ^{137}Cs at the calibration laboratory. Hence, the equation (1) is transformed to

$$\mathrm{Hp(d) = C_p(E)\,.N\,.\,CF(662keV).\frac{1}{F(E)}} \qquad (3)$$

In the above equation, the detector's response function F(E) is used as an energy correction factor of radiation field. Figure 3 shows the simulation result of relative energy response function F(E) for a silicon PIN photo diode using Al filter.

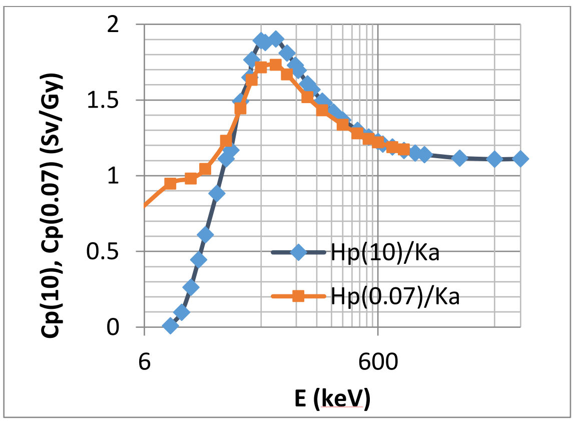

Fig.1. Conversion coefficients from air kerma Ka to Hp(10) and Hp(0.07)

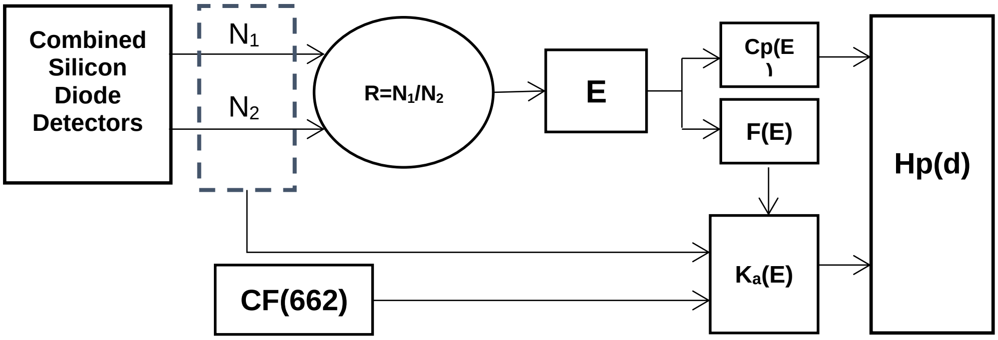

Fig.2. Hp(d) Evaluating algorithm of energy correction method

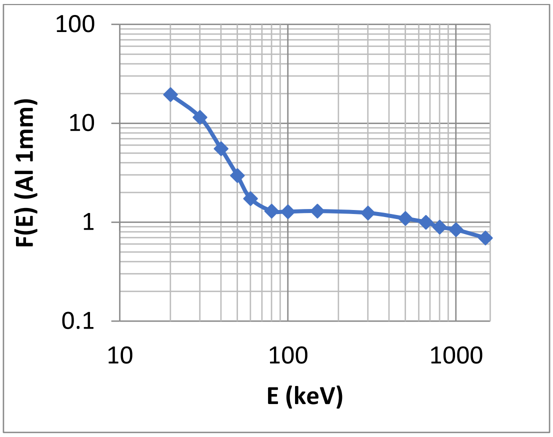

Fig. 3. Relative energy response function of detector

However, it is necessary to know information on photon energy in order to consider the response characteristics and dose conversion coefficient as a function of their energy dependence. Additional, the methods used to determine the energy of incident photon based on spectral distribution are not of practical application routinely. Thus, the purpose of this work is to develop an alternative method to estimate effective energy of radiation beam, as Tandem method. The basic principle of method is based on the absorption effect in the different materials of incident radiation. The narrow, monotonic beam of radiation passing through the filter is attenuated in the exponential law and depends on the energy of radiation beam. So with the different filter configurations, from the ratio of counts from two detectors, information on the photon energy can be derived. Assuming that the counts collected by detector 1, 2 are N_1, N_2, the ratio is described by

$$R = \frac{N_1}{N_2} = f(E) \qquad (4)$$

Equation (4) are established on the premise that the detection system meets the narrow-beam geometry. Under broad-beam geometry conditions, the influence of the scattered photons must be considered. By Monte Carlo simulation, the calculations are performed to demonstrate for determining ratio of detectors using different filters including 1mm aluminium and 1.5 mm aluminium + 0.3mm tin. The obtained result illustrated in fig.4 shows a relationship between R and the beam energy.

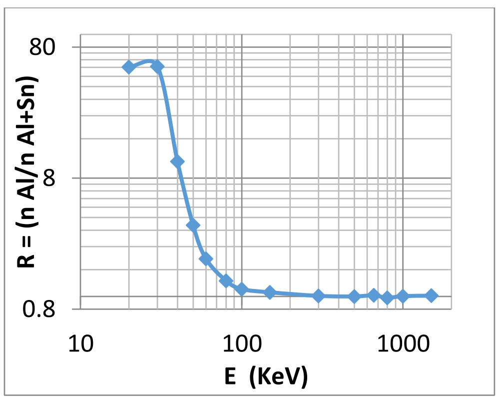

Fig. 4. The relationship of ratio of counts and photon beam energy

Based on calculation results, the ratio of counts detected by two detector is a function of energy and can be expressed by

$$\ln(E) = 4{,}6997 - 1{,}1263\ln(R) + 0{,}453\ln(R)^2 - \\ - 0{,}0659\ \ln(R)^3 \qquad (5)$$

For the case of incident radiation energy greater than 200 keV, the ratio is approximately 1 corresponding to energy of 662 keV. Therefore, the dose conversion coefficient Cp(E) and energy response F(E) can be determined through the energy value given by Eq.5. Also, the value of Hp (d) can be easily obtained.

B. Fitted-shape method

In actual field conditions, the energy of the photons is not known. The aim of this method described here is to discuss how the difficulty encountered in the above method can be overcome in a different approach. In the effect of the radiation field, that is, to the count readings N, of the detectors worn by the exposed individual, and air kerma, Ka, have the following relation analogous to following equation

$$N = R(E).K_a(E) \qquad (6)$$

where R(E) is energy dependent detector response function in units of counts per unit air kerma. Equation (6) implies that N, is proportional to air kerma in the case of monodirectional monoenergetic radiation fields. Most detectors for photons have this property. Note the similarity in form between Eqs. (1) and (6). Assuming that the photon field are identical, it has been shown that matching the shape of a detector’s energy response curve to the kerma-to-personal dose equivalent conversion function provides an approximate means of determining the dose equivalent without the need to resolve the actual incident energies. As long as R(E) has a similar energy response to that of $C_p(E)$, the dosimeter measurement can be said to be accurate. Based on this design philosophy, the ratio determined by:

$$\frac{Hp(d)}{N} = \frac{C_p(E)}{R(E)} = k \qquad (7)$$

is termed dose calibration constant k[Sv/Cnt], which defines the traditional energy response of the dosimeter in terms of dose equivalent per unit count. This is a quantitative formulation of a design criterion for detectors. Assuming such a fitted dosimeter system, one immediately obtains

$$Hp(d) = k.N \qquad (8)$$

This is the relationship being sought between H and N. It is significant for arbitrary movements of the individual within radiation fields with variable energy spectra. The detector response function, R(E), can be determined in monoenergetic, monodirectional radiation fields. In order to measure Hp(d) according to equation (8) the dose calibration constant k must be determined from equation (7). In order to satisfy equation (7), the following “fitting procedure” is carried through. The algorithm of these determination and fitting procedure are implemented as shown in fig. 5.

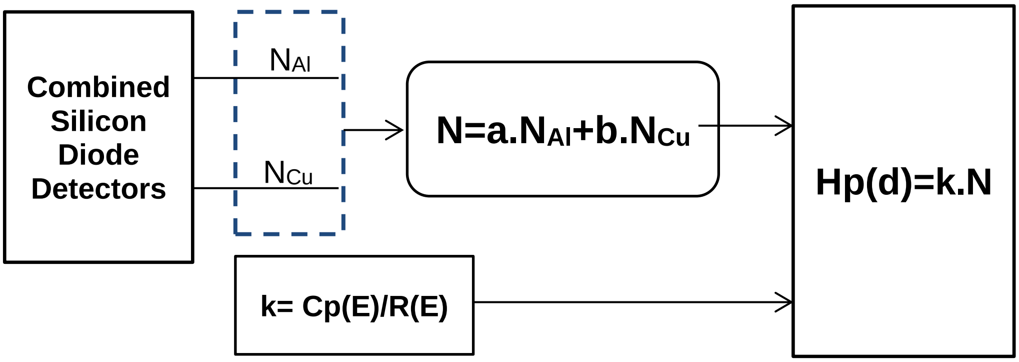

Fig.5. Hp(d) Evaluating Algorithm of Fitting-shape Method

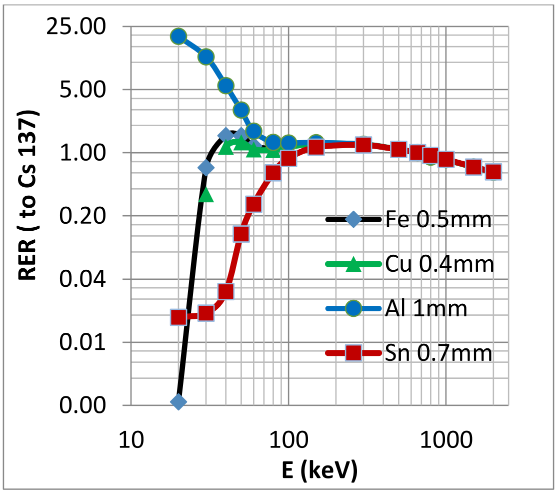

Fig.6. Filtered detector's response

Based on the evaluation results of the metal filtered silicon (PIN) diode detector relative energy response (RER) as shown in fig.6 by Monte Carlo radiation transport methods and the known shape of the kerma to personal dose equivalent conversion function curve, this dose calculation algorithm is implemented mathematically by combining the signals of the two silicon diode detectors with different filters, 1 mm Al and 0.6 mm Cu, expressed by N_{Al} and N_{Cu} counters. The linear combination of counts and the coresponding responses are determined by:

$$N = a.N_{Al} + b.N_{Cu} \qquad (9)$$

and

$$R(E) = a.R_{Al}(E) + b.R_{Cu}(E) \qquad (10)$$

From Eqs. (7) and (10), this method involves solving the following equations

$$C_p(E) = k.(a.R_{Al}(E) + b.R_{Cu}(E)) \qquad (11)$$

for the desired energy range. The constants a, b and k in equation (11) are obtained by using the 3D least square fit method of the curve fitting z=ax+by where $z=C_p(E)$, $x=R_{Al}(E)$ and $y=R_{Cu}(E)$. The practical values and formulation of Hp(d) for application will be calculated in detail in the experimental part.

III. EXPERIMENTAL RESULTS

In the experimental part, we considered and carried out in detailed only the algorithm of fitted-shape method by its advantages in compared with the energy correction method for evaluating the Hp(d) quantities. The prototype EPD has been built and an experimental setup is shown in Fig. 7 with the hardware consists of the following parts.

- ❑ Two filtered Si-PIN diode detectors
- ❑ Pre-Amplifier
- ❑ Pulse Shaper

- Pulse Discriminator
- Counter 1, 2 and Microcontroller
- RS-232 Interface and PC

The Si-PIN photodiode detector generates the pulse charge output by the incident photon. The charge is converted to voltage by the charge pre-amplifier. The long-width signal is converted to a practical pulse signal by using a shaping amplifier, and then to logic pulse for digital counting by discriminator. Microcontroller counts the pulses from two independent channels of Si-PIN photodiode detectors to obtain the count rate [cpm], which were transmitted to the PC by serial communication RS-232 for calculation.

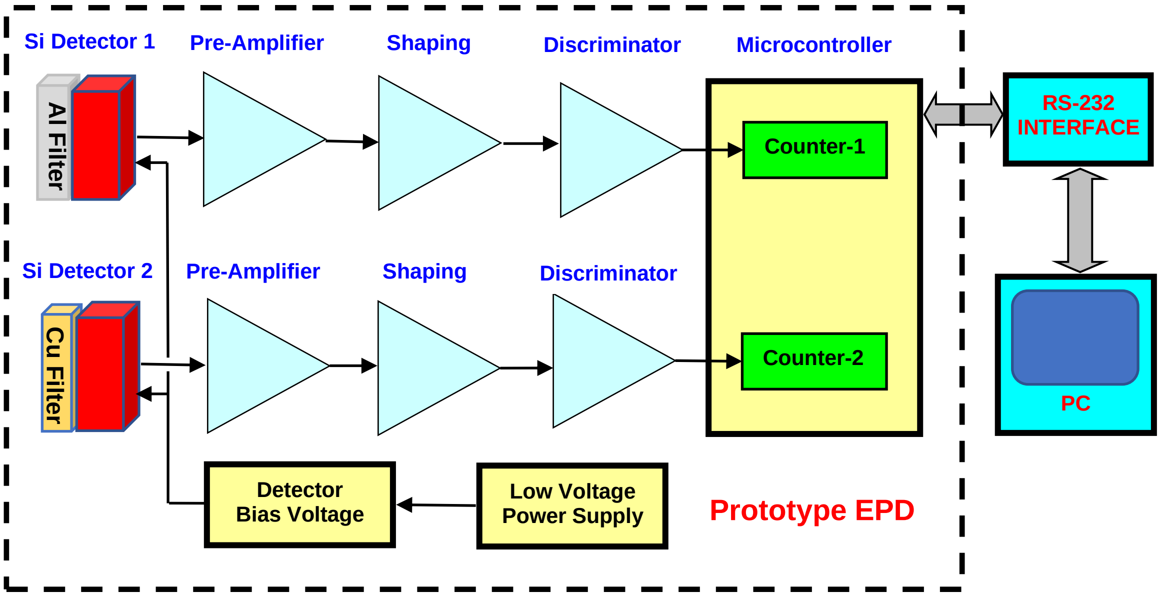

Fig.7. Experimental Hardware Block Diagram

To investigate the dosimetry characteristics of the method, experiments were performed for an actual photon radiation field. The prototype EPD was located in the front of the ISO PMMA Phantom (30x30x15 cm^3) and the Si detectors was coincident with the center of the reference radiation fields at the Secondary Standard Dosimetry Laboratory (SSDL) of Institute for Nuclear Science and Technology (INST). The experimental data has been obtained by performing irradiation according to the following characteristics of reference radiation field. A low-energy reference radiation is based on the narrow-spectrum series of the ISO Standard 4037-1 produced by an X-ray machine. The narrow-spectrum series used in the research described in this paper mainly include N-30 (24 keV), N-40 (33 keV), N-60 (48 keV), N-80 (65 keV), and N-100 (83 keV) and a high-energy reference radiation is based on ^{137}Cs (662 keV) and ^{60}Co (1.25 MeV) isotope radiation sources. Measurement results of the Al and Cu filtered detector's energy responses on air-kerma rate are shown in table I and illustrated on Fig. 8. From these data, the fitting procedures by least square fit were carried out in case of $C_p(10)$ according to equation (11) and the linear combination response $R_{10}(E)$ of two practical responses were obtained for two energy ranges based on ratios of $R_{Al}/R_{Cu}>1$ (E<100 keV) and $R_{Al}/R_{Cu} \leq 1$ (E$\geq$100 keV) as follows.

For E<100 keV:

$$R_{10}(E) = (0.0712\ R_{AL}(E)+0.0093\ R_{Cu}(E)) \quad (12)$$

For E≥100 keV:

$$R_{10}(E) = (-14.2683\ R_{Al}(E)+14.5254\ R_{Cu}(E))(13)$$

The calculated ratios shown in table II with error less than 25% from average one show good matching or similarity of combined response and conversion function (Fig.9). The formulation of Hp(10) quantities are given in Eqs. (14) and (15).

For E<100 keV:

$$Hp(10) = 0.102\ (0.0712N_{Al}+0.0093N_{Cu}) \quad (14)$$

Table I.

E (keV)	R_{Al} cpm/(μGy/h))	R_{Cu} (cpm/(μGy/h))	Ratio R_{Al}/ R_{Cu}
0	81.9	0.004	20475
33	152.97	0.643	237.9
48	262.66	84.811	3.1
65	268.98	193.38	1.39
83	314.57	310.311	1.01
662	54.15	54.15	1
1250	33.67	33.67	1

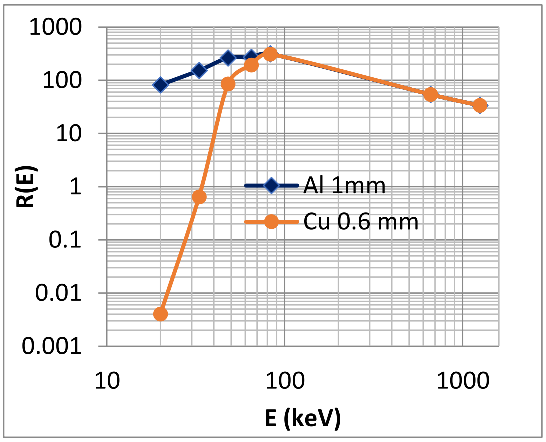

Fig. 8. Energy responses of Al and Cu filtered silicon diode detectors

For E≥100 keV:

$$Hp(10) = 0.110(-14.2683N_{Al}+14.5254\ N_{Cu})\ (15)$$

Table II.

E (keV)	$R_{10}(E)$	Ratio $k=C_p(10)/R_{10}(E)$	Error (%)
20	5.83	0.105	2.69
33	10.89	0.107	5.33
48	17.92	0.092	9.71
65	17.36	0.108	6.21
83	19.51	0.097	4.52
661	13.92	0.087	20.90
1250	8.66	0.133	20.90
Average of Ratios (E<100 keV)		**0.102**	
Average of Ratios (E>100 keV)		**0.110**	

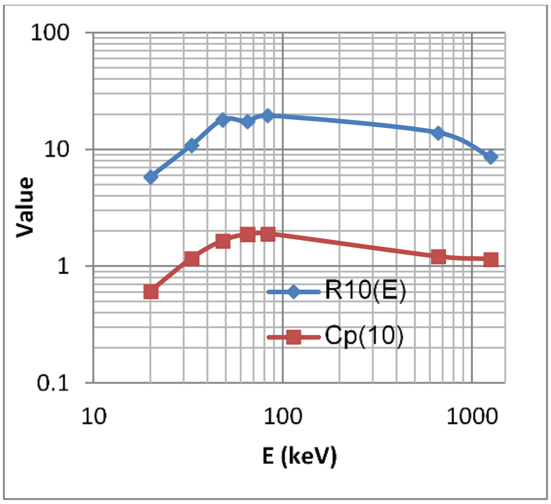

Fig. 9. Similarity of combined response $R_{10}(E)$ and conversion function $C_p(10)$

The same procedures have also been done for the case of $C_p(0.07)$ to determine combination response $R_{0.07}(E)$ in Eqs. (16), (17) and the formulation of Hp(0.07) quantities are given in Eqs. (18) and (19).

For E<100 keV:

$R_{0.07}(E)=(0.08034\ R_{Al}(E)+0.02734\ R_{Cu}(E))$ (16)

For E≥100 keV:

$R_{0.07}(E)=(-13.9696\ R_{Al}(E)+14.1553\ R_{Cu}(E))$ (17)

For E<100 keV:

$Hp(0.07)=0.111(0.08034\ N_{Al}+0.02734\ N_{Cu})$ (18)

For E≥100 keV:

$Hp(0.07)=0.142\ (-13.9696\ N_{Al}+14.1553\ N_{Cu})$ (19)

Table III.

E (keV)	$R_{0.07}(E)$	Ratio $k=C_p(0.07)/R_{0.07}(E)$	Error (%)
20	6.58	0.159	42.68
33	12.27	0.106	4.84
48	18.78	0.085	23.48
65	16.32	0.105	5.33
83	16.79	0.101	9.03
661	10.06	0.119	15.98
1250	6.25	0.165	15.98
Average of Ratios (E<100 keV)		**0.111**	
Average of Ratios (E>100 keV)		**0.142**	

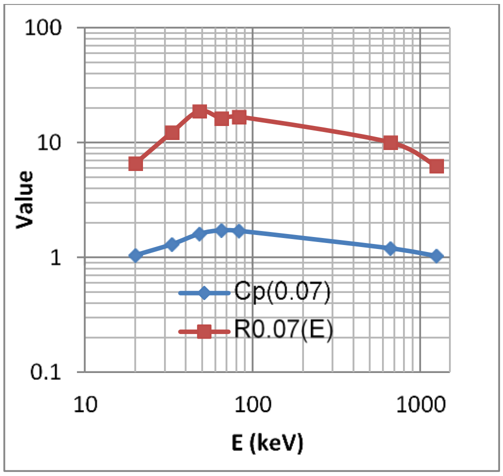

Fig. 10. Similarity of combined response $R_{0.07}(E)$ and conversion function $C_p(0.07)$

Table IV.

Energy (keV)	Kerma (µGy)	Delivered Hp(10) (µSv)	Counts N_{Al}	Counts N_{Cu}	Measured Hp(10) (µSv)	Error (%)	Delivered Hp(0.07) (µSv)	Measured Hp(0.07) (µSv)	Error (%)
20	483.18	295.22	43638	2	317.03	**7.4**	504.92	390.25	**22.7**
	996.91	609.11	83790	2	608.75	**0.1**	1041.77	749.35	**28.1**
33	259.09	303.14	45880	127	333.21	**9.9**	336.82	409.93	**21.7**
	534.28	625.11	83465	381	606.03	**3.1**	694.56	745.29	**7.3**
	847.82	991.95	106485	647	773.02	**22.1**	1102.16	950.35	**13.8**
48	290.85	479.90	76777	25086	533.91	**11.3**	465.36	610.27	**31.1**
	438.15	722.94	97673	33388	677.82	**6.2**	701.04	771.88	**10.1**
65	321.21	603.87	89257	44931	605.69	**0.3**	552.48	661.48	**19.7**
	404.54	760.54	98412	49586	667.77	**12.2**	695.81	729.18	**4.8**
	449.46	844.99	102782	51814	697.40	**17.5**	773.08	761.49	**1.5**
83	322.44	612.63	87395	74433	564.07	**7.9**	548.15	555.03	**1.3**
	491.05	932.99	104081	92261	668.32	**28.4**	834.78	649.98	**22.1**
662	50.00	60.50	2830	2830	80.14	**32.5**	60.00	74.64	**24.4**
	125.00	151.25	6956	6956	196.97	**30.2**	150.00	183.47	**22.3**
	500.00	605.00	25334	25334	717.37	**18.6**	600.00	668.20	**11.4**
	833.33	1008.33	37554	37554	1063.41	**5.5**	1000.00	990.52	**0.9**
	1250.00	1512.50	54354	54354	1539.13	**1.8**	1500.00	1433.63	**4.4**
1250	2.16	2.48	71	71	2.02	**18.6**	2.22	1.88	**15.3**
	4.40	5.06	141	141	3.99	**21.1**	4.53	3.72	**17.9**
	1.28	1.47	46	46	1.30	**11.6**	1.31	1.21	**8.1**

It is can be seen from the obtained Eqs. (14), (15), (18) and (19) that the personal dose equivalents Hp(d) have a simple one-to-one relationship with the counting numbers of pulses acquired from two detectors. To confirm the validity of the algorithm, the accumulated doses were evaluated from prototype EPD exposed to the beams with delivered doses from different air-kerma rate for 1 minute using the formulas above and count readings for calculating Hp(d). The obtained results of personal dose equivalents are given in tables IV with errors almost less than 30% between delivered and measured ones in energy range from 20 keV to 1.25 MeV. In this study, all the fitted parameters and calibration constant k were determined above in experimental time for evaluating personal dose equivalents. In general case of calculation of dose equivalents based on Eq (8), beside of the energy-dependant counting number N which is not changed as characteristic of detector's silicon material, however, the factor k as sensitivity of EPD should be recalibrated periodically to ensure the accuracy of the measurement.

IV. CONCLUSIONS

In this paper, the measurement methods and dose evaluating algorithms for electronic personal dosimeter were described in detail. The testing of the algorithm for prototype EPD exposed by the beam of radiation defined in ISO 4037-1 at SSDL of INST shows good results of personal dose equivalents are partially met the EPD design requirements according to the IEC 61526 Standard and proving the suitability of the algorithm for evaluating personal dose equivalents. This paper does not include information from the angular response of the dosimeter. This, however, is foreseen to be carried out in a further step.

The work and results of described are important basics for design and construction of completed electronic personal dosimeter.

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