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USING A SCANNER TO MEASURE ABSORBED DOSES WITH RADIOCHROMIC FILM DOSIMETERS[†]

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The article provides a sequence of steps for using RISØ calorimeters for calibration and subsequent use of B3 radiochromic film dosimeters (GEX corporation) and a scanner for measuring absorbed doses. Calibration was carried out with the help of electron beam accelerator in the range of absorbed doses of 3 – 40 kGy (measurement range of RISØ calorimeters).
In the course of the work, the following was carried out:

- calibration of B3 radiochromic dosimetry films using RISØ calorimeters;
- plotting a calibration curve for B3 radiochromic dosimetric films;
- calculation of approximation functions;
- development of a technique for using a flatbed scanner to measure absorbed doses;
- estimation of the measurement uncertainties of absorbed doses.

Accelerator operation parameters: scanning frequency of the accelerated electron beam – 5 Hz, pulse frequency – 120 Hz, electron energy – 5 MeV, electron beam current – 60 μA. The measurement error of the absorbed dose is 5.8 %.

Keywords: absorbed dose, calorimeter, radiochromic dosimetry films, scanner, uncertainty.
PACS: 06.20.-f; 29.40.Vj; 29.40.Wk

INTRODUCTION

Measurement of absorbed doses is an important and indispensable task in radiation processing operations. The absorbed dose is the main criterion for assessing the degree of radiation processing of materials. There are several ways to measure the absorbed dose, which can be roughly divided into two categories: physical and chemical. But one of the most widespread methods of measuring doses in recent years has become a method using radiochromic films. The reason for this popularity is the simplicity and convenience of measurements. The measurement of absorbed doses by radiochromic films is based on the change in the color of the films depending on the absorbed dose. Spectrophotometers are used to measure the color change. In works [1, 2] examples of using office scanners for measuring absorbed doses by B3 film dosimeters are given.

This article provides a sequence of actions for the possibility of using B3 film dosimeters to measure absorbed doses at an electron accelerator in accordance with the relevant standards given above.

INITIAL EVALUATION OF CALORIMETER PERFORMANCE

In the course of this work, we used dosimeters No 1856, 1935, 1936 manufactured by RISØ. Doses were originally measured for a conveyor speed $v_d = 0.6$ mm/sec. The results of measurements of the absorbed dose are shown in Table 1.

Based on the initial dose measurements given in Table 1, it was decided not to use calorimeter No. 1856 for calibrating film dosimeters, since the readings of this dosimeter differ from the others by almost 2 %, while the difference between dosimeters No. 1935 and No. 1936 is less than 1 %.

THE PROCEDURE FOR MEASURING THE ABSORBED DOSE WITH CALORIMETERS

In accordance with § 8.1.5 of ISO/ASTM 51631: 2013(E) Practice for use of calorimetric dosimetry systems for electron beam dose measurements and dosimetry system calibrations, after the calorimeters passed through the irradiation zone, the time elapsed since the end of the dosimeter and the resistance was recorded [3]. The measurement data are shown in Table 2

The data from Table 2 are presented in Fig. 1. To determine the resistance at the end of the irradiation,

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Table 1: Initial measurement of absorbed doses with calorimeters.

Dosimeter no.	Resistance before irradiation, Ohm	Temperature before irradiation, °C	Resistance after irradiation, Ohm	Temperature after irradiation, °C	**Absorbed dose, kGy**
1935	2185	22.68	796	50.63	**38.11**
1936	2218	22.33	789	50.63	**38.54**
1856	2127	23.40	779	51.31	**37.42**

Table 2: Dependence of the calorimeter resistance R on the time t that has passed since the end of the irradiation.

Time t, min	Resistance R, Ohm	
	Dosimeter No	
	1935	1936
1	792	799
2	795	802
3	798	805
4	803	809
5	809	815
6	816	821
7	824	828
8	833	836
9	842	844
10	851	853
12	872	871
15	905	900
18	940	932
20	965	954

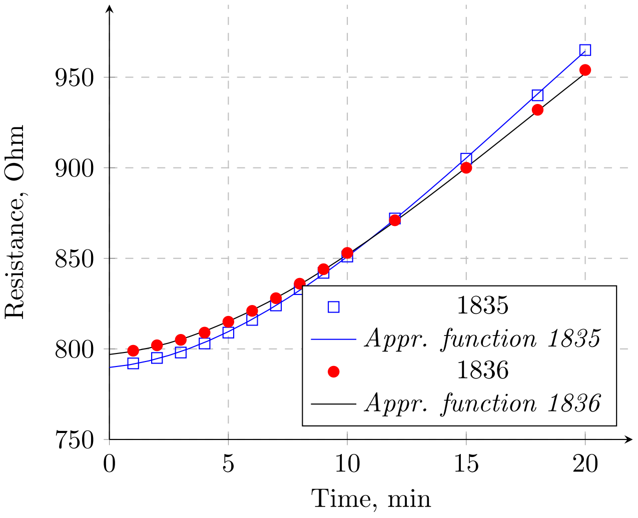

Figure 1: The dependence of the resistance of the calorimeters on the time elapsed since the end of the irradiation.

it is necessary to extrapolate the approximating functions shown in Fig. 1. To determine the type of the approximating function, we used the ROOT statistical package (`https://root.cern/`). For dosimeter No. 1835, the following approximating function was obtained:

$$R(t) = -0.011464 \cdot t^3 + 0.605339 \cdot t^2 + 1.208758 \cdot t + 789.785827 \quad (1)$$

For dosimeter No. 1836, the following approximating function was obtained:

$$R(t) = -0.009683 \cdot t^3 + 0.520607 \cdot t^2 + 1.292768 \cdot t + 796.933373 \quad (2)$$

Based on Table 2 and formulas (1, 2), we compose Table 3 of the change in resistance ΔR with time t.

Table 3: Dependence of the change in the resistance of the calorimeters ΔR on the time t that has passed since the end of the irradiation.

Time, min	ΔR, Ohm No of dosemeter 1935	 1936
1	2	2
2	5	5
3	8	8
4	13	12
5	19	18
6	26	24
7	34	31
8	43	39
9	52	47
10	61	56
12	82	74
15	115	103
18	150	135
20	175	157

Thus, to determine the resistance of the calorimeter at the time of the end of its irradiation, it is necessary to measure the time elapsed from the end of the irradiation to the start of the resistance measurement. From Table 3, proceeding from the time from the end of irradiation to the beginning of measurement, the correction ΔR is determined, which is subtracted from the measured resistance of the calorimeter. And, thus, the value of the resistance of the calorimeter at the moment of the end of the irradiation is obtained.

MEASUREMENT OF ABSORBED DOSES FOR DIFFERENT CONVEYOR SPEEDS AND PREPARATION OF CALIBRATION RADIOCHROMIC FILM DOSIMETERS

The calorimeters were placed in aluminum containers at a distance of 6 cm from the edge of the container on foam stands (about 1 cm high) to avoid heating the calorimeter from the container. The container was positioned at a distance of 20 cm from the edge of the conveyor. A phantom was first placed on the container, then a calorimeter. Radiochromic film dosimeters were located in phantoms, between two polystyrene plates, marked with the letter "A" in Fig. 2.

The results of measuring the absorbed doses for different conveyor speeds are shown in Table 4.

Four film dosimeters were used for each value of the absorbed dose. Each dosimeter was scanned with a resolution of 1200 dpi, and using the written Python code, the green channel was highlighted (in the form of values of gray) and the gray value was determined using the GIMP graphical editor. For each conveyor speed, the absorbed dose was averaged and these gray values entered in Table 5.

GETTING THE CALIBRATION FUNCTION

To obtain a calibration curve, it is necessary to convert the dose-signal data into a smooth function. For this, you can use statistical software packages. In this work, we used the ROOT data handling package (CERN, `https://root.cern/`). In accordance with the recommendations given in NPL Report CIRM 29 [4], the selection of the calibration function is performed starting with a polynomial of the 1st degree. For this, the function is searched for in the polynomial form $Dose = f(signal)$. To select the degree of the polynomial function, "persentage residuals" are calculated using the formula:

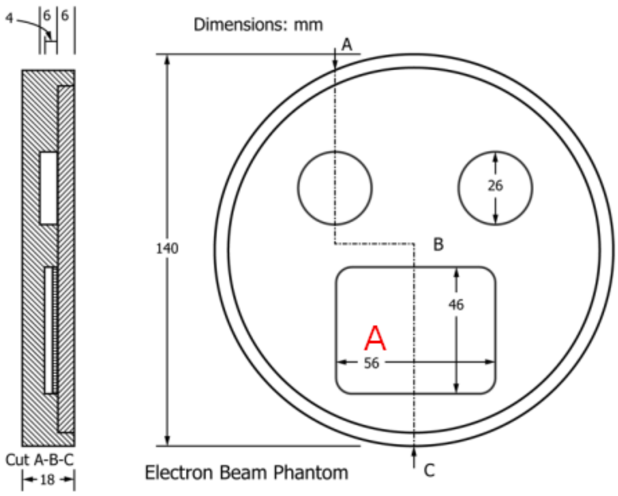

Figure 2: Phantom for irradiation of routine dosimeters. The letter "A" denotes the location of the film dosimeters.

$$\frac{D_{calculated}-D_{delivered}}{D_{delivered}}\cdot 100 \tag{3}$$

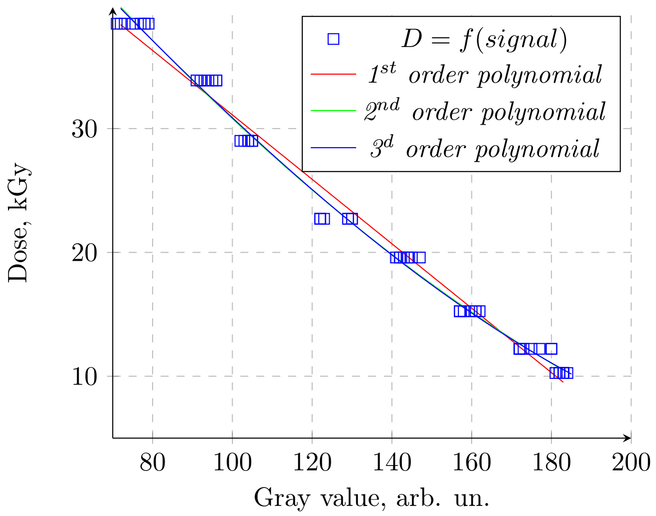

Figure 3: Dose versus gray value and approximation curves.

It can be seen from Fig. 3 that the 1st order polynomial approximates the points on the graph less well. Therefore, the calibration (approximating) function will be sought in the form of polynomials of the 2nd or 3rd orders. Figures 4and 5 show the percentage deviations depending on the dose. The largest deviation was for the 2nd degree polynomial (9.53 %). For the 3rd degree polynomial, the maximum deviation was 9.37 %.

Therefore, a third-degree polynomial was chosen for the calibration function in the dose range of 10 – 40 kGy:

$$Dose = 1.55466\cdot 10^{-6}\cdot x^3 + 8.14774\cdot 10^{-5}\cdot x^2 - 0.364245\cdot x + 64.92610, \tag{4}$$

where, *Dose* is the absorbed dose, kGy; x is the gray value, arbitrary units.

Carrying out similar calculations, for a dose range of 3 – 10 kGy, we obtain the following calibration function:

$$Dose = 7.55213\cdot 10^{-6}\cdot x^3 - 0.00189324\cdot x^2 - 0.332016\cdot x + 87.5538, \tag{5}$$

Fig. 6 shows the dependence of the dose on the gray value and the approximation curves of the 3rd order polynomial. The dose range is 3 – 10 kGy.

Table 4: Absorbed dose values for different conveyor speeds.

No of dosemeter	Conveyor speed, mm/s	Resistance before irradiation, Ohm	Resistance after irradiation, Ohm	Time after irradiation, min	Real resistance after irradiation, Ohm	**Absorbed dose, kGy**
			10 – 40 kGy			
1935	0.6	2130	777	1,0	775	**38,40**
1936		2183	790	1,0	788	**38,54**
1935	0.7	2180	863	1,0	861	**34,18**
1936		2173	880	1,0	878	**33,60**
1935	0.8	2219	982	1,0	980	**29,25**
1936		2201	995	1,0	993	**28,77**
1935	1.0	2162	1130	1,0	1128	**22,78**
1936		2170	1145	1,0	1143	**22,61**
1935	1.2	2166	1230	1,0	1228	**19,54**
1936		2161	1231	1,0	1229	**19,64**
1935	1.5	2158	1374	1,5	1371	**15,31**
1936		2161	1385	1,0	1383	**15,19**
1935	1.9	2254	1548	1,0	1546	**12,35**
1936		2230	1551	1,0	1549	**12,07**
1935	2.3	2183	1598	1,0	1596	**10,24**
1936		2175	1596	1,0	1594	**10,27**
			3 – 10 kGy			
1935	2.4	2123	1590	1,0	1588	**9,56**
1936		2098	1581	1,0	1579	**9,46**
1935	3.0	2071	1643	1,0	1641	**7,63**
1936		2080	1653	1,0	1651	**7,63**
1935	3.6	2064	1695	1,0	1693	**6,45**
1936		2045	1692	1,0	1690	**6,28**
1935	5.0	2088	1808	1,5	1805	**4,66**
1936		2077	1799	1,0	1797	**4,68**
1935	7.0	2077	1868	1,0	1866	**3,39**
1936		2073	1869	1,0	1867	**3,34**

UNCERTAINTY ESTIMATION

To estimate uncertainty, all possible sources of uncertainty must first be identified and then quantified.

When measurements are associated with statistical effects such as random variation between individual dosimeters, errors are referred to as "Type A" errors. The other component of the error, such as the effect of

Table 5: Gray values for different absorbed doses.

Dose, kGy	Gray values							
	Film dosemeter No							
	I	II	III	IV	V	VI	VII	VIII
10 – 40 kGy								
38,47	77	78	79	78	75	71	73	72
33.89	94	96	96	95	91	92	93	92
29.01	102	105	105	104	104	103	105	104
22.71	122	123	122	122	129	130	129	130
19.59	144	147	145	144	142	141	142	143
15.25	158	157	157	157	161	161	162	160
12.21	172	173	172	172	175	180	177	180
10.26	184	183	182	183	183	181	182	183
3 – 10 kGy								
9.51	185	183	184	186	185	185	185	185
7.63	192	192	191	192	187	188	188	187
6.37	202	202	202	202	197	196	196	195
4.67	205	204	205	204	209	208	207	208
3.37	215	214	213	215	222	221	221	221

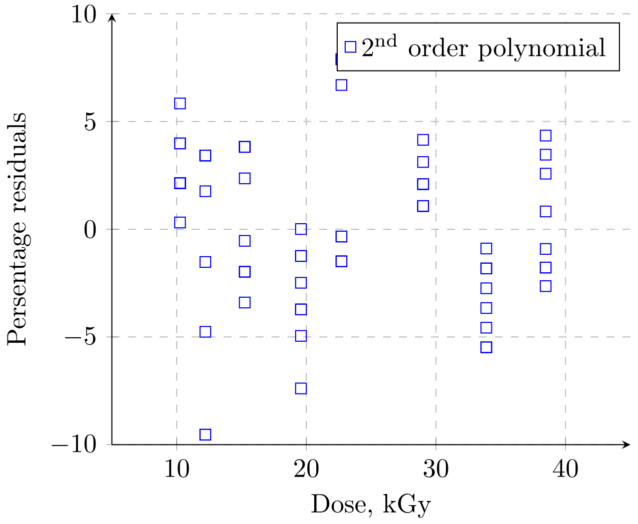

Figure 4: Percentage residual as a function of dose for the 2^{nd} order approximation polynomial. Dose range 10 – 40 kGy.

the dose rate on the response of the dosimeter, for example, cannot be measured directly. This error is "Type B".

Let us consider the types of uncertainties in measuring the absorbed dose.

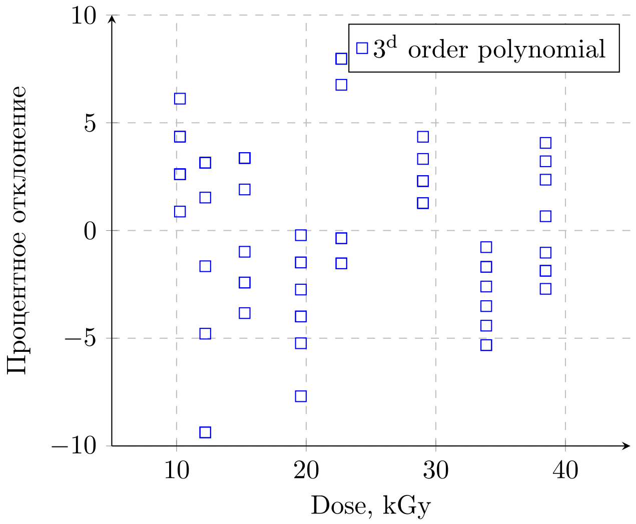

Figure 5: Percentage residual as a function of dose for the 3^{d} order approximation polynomial. Dose range 10 – 40 kGy.

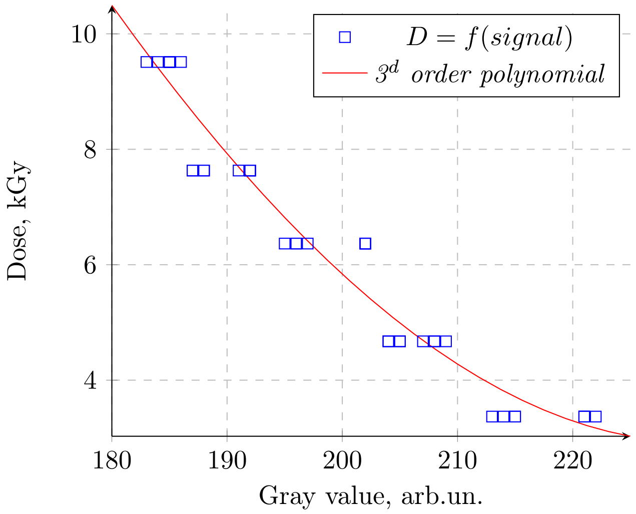

Figure 6: Dose versus gray value and approximation curves of the 3^{rd} order polynomial. Dose range 3 – 10 kGy.

Uncertainty in determining the calibration function

Instrument uncertainty

The resistance of the calorimeters was measured with a METEX M32700 multimeter with a measurement error of 0.8 %.

Uncertainty in the manufacturing of calibrated dosimeters

The inconsistency in the placement of calibrated dosimeters inside the phantom can introduce an error in the absorbed dose. This applies especially to electron accelerators. Since the phantom was installed using a tape measure twice (one time it waswhen - the phantom was installed relative to the container, and the second time - when the container was installed relative to the conveyor), then double half of the roulette division unit - 1 mm is taken as the permissible error. The dosimeters in the phantom were located in the middle; we assume the error in this case is 5 mm. In accordance with the electron beam homogeneity test, the variability of the absorbed dose in the center of the beam within 1 cm is about 1.5 %.

Uncertainty when fitting the calibration function

As recommended in NPL Report CIRM 29 [4], the error in fitting the calibration function was defined as the root-mean-square percentage deviation. In this case, the percentage deviation was averaged for each dose value. Applying the above method, we obtain an error in fitting the calibration function equal to 2.5 %.

Uncertainties associated with the variability of the irradiation process

During irradiation, the beam energy, beam current, etc. can change. The instructions for the accelerator indicate that the uniformity of the dose along the scan length is ± 5 %.

Resultant uncertainty

The summary table, taking into account all uncertainties, is as follows:

Table 6: The summary table of uncertainties.

Type of the uncertainty	Uncertainty, %
Instrument uncertainty	0,8
Uncertainty in the manufacture of calibrated dosimeters	1,5
Uncertainty when fitting the calibration function	2,5
Uncertainties associated with the variability of the irradiation process	5,0

To calculate the combined uncertainty, we use the following formula (NPL Report CIRM 29 [4]):

$$u_c = \sqrt{u_1^2 + u_2^2 \dots u_i^2}.$$

Substituting the uncertainties values from Table 6, we obtain the following value of the combined uncertainty:

$$u_c = 5,8\ \%.$$

1 Sequence of actions when measuring the absorbed dose using a scanner

1. After irradiation, scan the dosimeter with a resolution of 1200 dpi.
2. Open the resulting file in GIMP. Press the right mouse button on the image. Then:
   Colors → Component → Decompose (fig. 7).
3. Uncheck "Decompose to layers" (fig. **??**)
4. Close all images, except for the image received from the green channel.
5. Instead of pp. 2-4, you can use the developed Python program "convertToGRayScale.py", which extracts a green channel from the image into a grayscale image . The format for using this program: from the command line, call
   python3 convertToGRayScale.py "filename.jpg".
   The result of the program will be a file with a grayscale image named "filename grayScale.jpg". Open the resulting file in the graphics editor GIMP and continue with 6.
6. Select the "Color picker tool". Enable checkboxes in the "Pick Target" menu in the "Pick only" and "Use info window" items (Fig. 9).
7. Left-click on the image and read the "V" readings in the "Pixel" section in the information window (Fig. 10). This is the gray value.
8. Substitute the obtained value into the formula (4) or (5) depending on the size of the measured dose.

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[*] For this program to work correctly, the *opencv-python* (`https://pypi.org/project/opencv-python/`) should be installed.

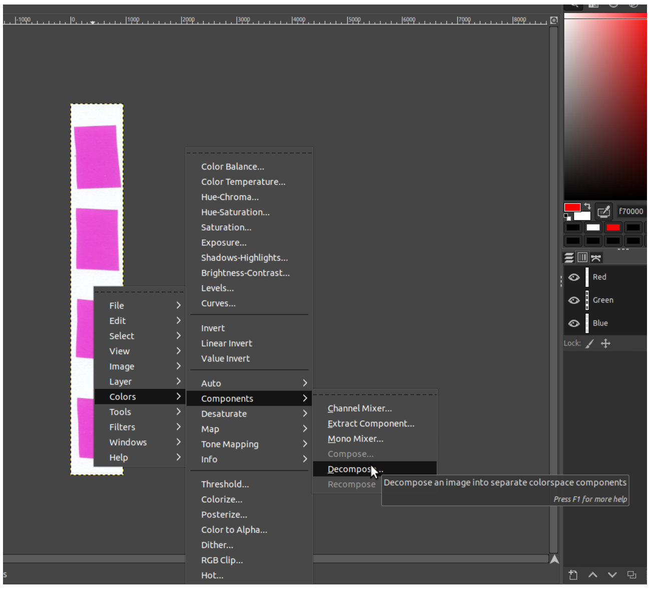
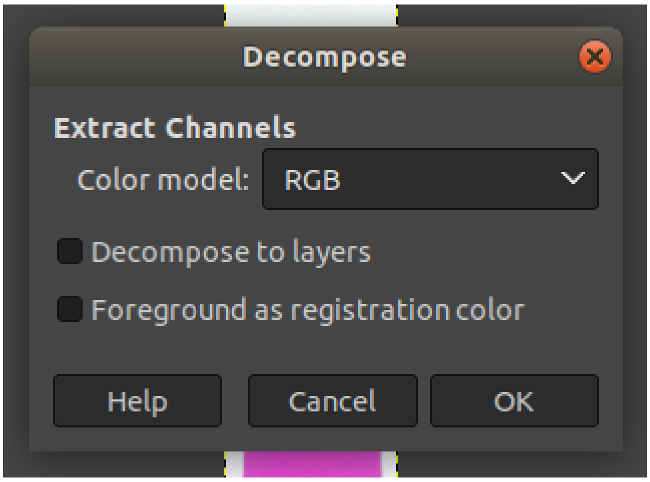


Figure 7: Color-coded image.



Extract Channels

Color model: RGB

☐ Decompose to layers

☐ Foreground as registration color

Figure 8: Decompose to layers.

CONCLUSION

Calibrated radiochromic dosimeters were received for the following doses: 38.47; 33.89; 29.01; 22.71; 19.59; 15.25; 12.21; 10.26; 9.51; 7.63; 6.37; 4.67; 3.37 kGy and a technique was developed for using the scanner to measure absorbed doses in the range of 3 – 10 kGy. For each dose, 4 film dosimeters were prepared. To calculate the absorbed dose by calorimeters, macros were developed for LibreOffice Calc and Microsoft Excel spreadsheets. All dosimeters were scanned and a green channel was highlighted using the developed program (the result was obtained in the form of an image in shades of gray). Using the graphical editor GIMP (https://www.gimp.org/), a gray value was determined for each dosimeter. In accordance with the recommendations given in NPL Report CIRM 29 [4], the measurement range of the RISØ calorimeter was divided into two areas: 10 – 40 kGy and 3 – 10 kGy. For each area, the dose dependences on the gray value were plotted and the approximation curves were obtained in the form of a third-order polynomial:

$$3 - 10\text{ kGy} - \qquad Dose = 7.55213 \cdot 10^{-6} \cdot x^3 - 0.00189324 \cdot x^2 - 0.332016 \cdot x + 87.5538,$$

$$10 - 40\text{ kGy} - \qquad Dose = 1.55466 \cdot 10^{-6} \cdot x^3 + 8.14774 \cdot 10^{-5} \cdot x^2 - 0.364245 \cdot x + 64.9261.$$

The uncertainty of the absorbed dose measurement is 5.8 %.

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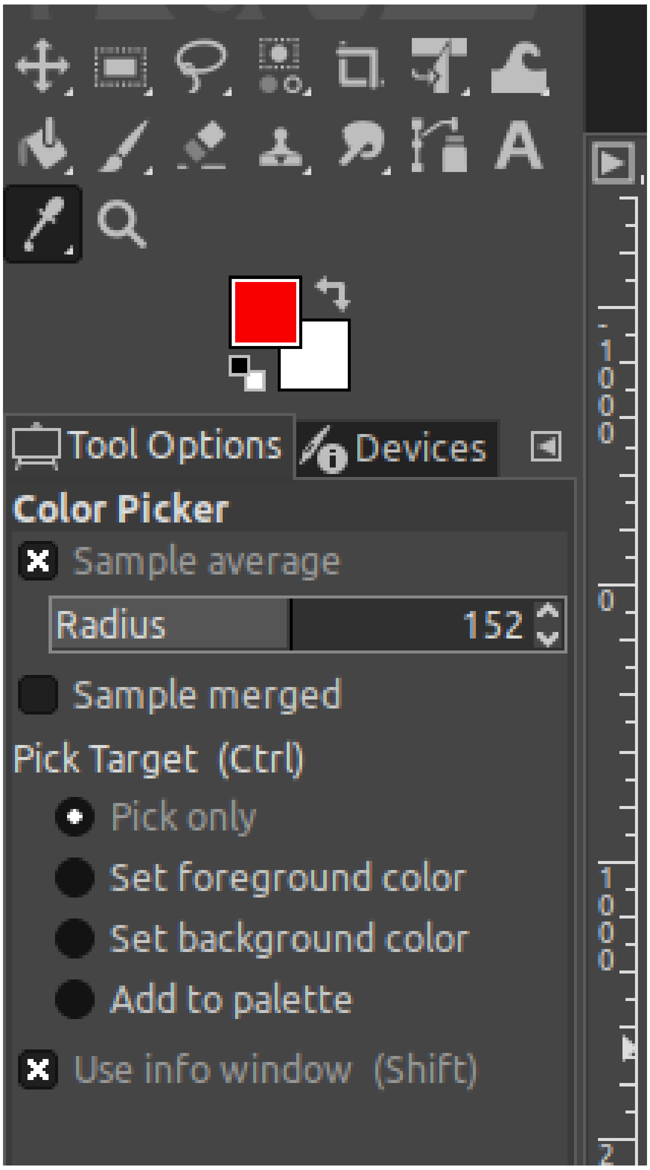


Color Picker

☒ Sample average

Radius 152

☐ Sample merged

Pick Target (Ctrl)

● Pick only

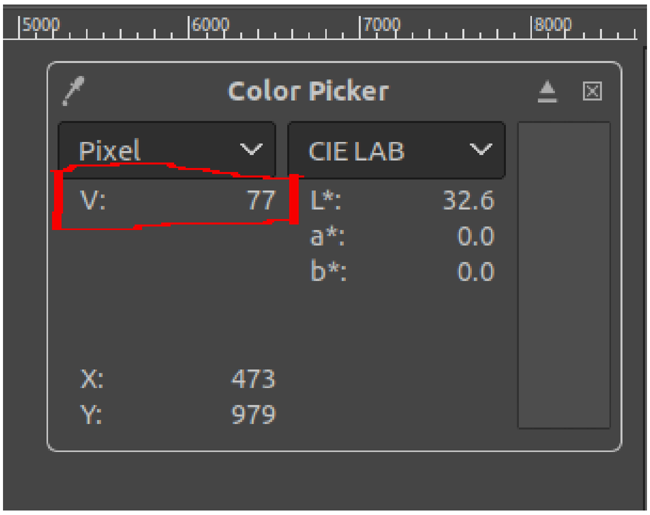
○ Set foreground color

○ Set background color

○ Add to palette

☒ Use info window (Shift)

Figure 9: "Color Picker" settings menu.



Color Picker

Pixel		CIE LAB	
V:	77	L*:	32.6
		a*:	0.0
		b*:	0.0
X:	473		
Y:	979		

Figure 10: Gray value.

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ВИКОРИСТАННЯ СКАНЕРА ДЛЯ ВИМІРЮВАННЯ ПОГЛИНЕНИХ ДОЗ РАДІОХРОМНИМИ ПЛІВКОВИМИ ДОЗИМЕТРАМИ

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У статті наведено послідовність етапів використання калориметрів RISØ для калібрування та подальшого використання радіохромних плівкових дозиметрів B3 (корпорація GEX) та сканера для вимірювання поглинених доз. Калібрування проводилося за допомогою електронного пучка в діапазоні поглинених доз 3 – 40 кГр (діапазон вимірювань RISØ калориметрів).

В ході роботи було проведено наступне:

- калібрування радіохромних дозиметричних плівок B3 за допомогою RISØ калориметрів;
- побудова калібрувальної кривої для радіохромних дозиметричних плівок B3;
- розрахунок апроксимаційних функцій;
- розробка методики використання планшетного сканера для вимірювання поглинених доз;
- оцінка невизначеності вимірювання поглинених доз.

Параметри роботи прискорювача: частота сканування пучка прискорених електронів – 5 Гц, частота імпульсів – 120 Гц, енергія електронів – 5 МеВ, струм електронного променя – 60 μА. Похибка вимірювання поглиненої дози становить 5,8 %.

Ключові слова: поглинена доза, калориметр, радіохромні дозиметричні плівки, сканер, невизначеність.