Experimental study of the possibility of 3D localization of the compact gamma-sources in soft tissues

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Abstract. To determine the depth of the area of radiopharmaceutical accumulation a method of simultaneous recording of two lines of gamma rays of different energies and quantitative comparison of the intensity of these lines on the surface of the patient’s body is provided. Since the coefficient of linear absorption of gamma radiation in the medium depends not only on the characteristics of the medium, but also on the gamma radiation energy, the intensity of gammas of different energies is attenuated differently after passing through the same absorber layer (soft tissues). Thus, the quantitative comparison of the relative intensities of gamma lines on the surface of the patient’s body allows to determine the depth of area of the accumulation of the radiopharmaceutical. The result is achieved by analyzing the energy spectrum of the source, obtained with a semiconductor spectrometer, by measuring the ratio of areas of the absorption peaks of the radioisotope and defining the depth of gamma source using the calibration dependence between the areas ratio and the medium layer thickness. The most widely used medical radioisotope technetium-99m has two gamma-lines - 140 keV and 18.5 keV, which allows one to apply the proposed method to search for the sentinel lymph nodes and non-palpable malignant tumors in the soft tissues.

1. Introduction
Radionuclide diagnostics is a branch of nuclear medicine, which currently is one of the most emerging types of the early stage cancer diagnosis [1]. Miniature gamma detectors, or gamma probes, are used to localize small and non-palpable malignant lesions. Intraoperative use of gamma probes for staging and evaluation of the extent of the malignant process is possible due to the structure and physiology of the human lymphatic system. Patient is injected with a radiolabeled nanocolloid, which accumulates in the first lymph node to which cancer cells are most likely to spread from a primary tumor [2]. Gamma probe detects radiation from the radiotracer, thus revealing the affected lymph nodes. One of the devices of such type, gamma-locator, has been developed in NRNU MEPhI [3].

The goal of the present work is to explore the possibility of three-dimensional localization of compact gamma sources with gamma-locator instead of determination of the 2D projection of the point of maximal radiotracer accumulation on the surface if the patient’s body.

2. 3D localization of the compact gamma-sources
If a medical gamma source has two or more emission lines and the energy resolution of detector is high enough, it is possible to measure the intensities of these lines at the surface of the patient’s body after passing through a layer of soft tissues. For example, the most commonly used radionuclide $^{99m}$Tc
has a 140 keV emission line, and also 18.5 keV x-rays. Quantitative comparison of the intensities of these lines allows to determine the depth of the point of the maximal radiotracer accumulation.

In a narrow beam geometry (without taking into account the scattered radiation), the radiation intensity can be calculated using the following equation:

\[ I = I_0 e^{-\mu x}, \]

where:  
- \( I \) – the intensity of gamma rays after passing through the slab of material,  
- \( I_0 \) – the initial intensity,  
- \( \mu \) – linear attenuation coefficient of the material,  
- \( x \) – thickness of the layer of the material.

Wide beam geometry is considered to take into account the effect of scattered radiation, which can be denoted as a so-called buildup factor \( B \). Buildup factor depends on the geometry of an experiment, properties of the material and energy of gamma-radiation. In that case the ratio of intensities of two gamma lines of different energies is:

\[ \frac{I_1}{I_2} = \frac{I_{01} e^{-\mu_1 x} B_{1}}{I_{02} e^{-\mu_2 x} B_{2} } = \frac{I_{01}}{I_{02}} e^{-(\mu_1 - \mu_2) x} B_{21}, \]

Where \( B_{21} \) is the total buildup factor.

To determine thickness of the soft tissues layer for 3D localization of a malignant formation the calibration of the dependence between the ratio \( I_1/I_2 \) and the layer thickness \( x \) is needed for a particular gamma detector, primarily because of the buildup factor which can not be determined analytically. Calibration can be performed with an acrylic or a water phantom. After that a gamma probe can be used to obtain a more detailed three dimensional information about placement and structure of the area of an increased radiotracer uptake in the patient’s body.

3. Experimental setup

For the feasibility study of the proposed method a \(^{137}\text{Cs}\) point-like gamma source, which has a 662 keV emission line (yield 85\%) and a 32 keV x-ray line (yield 6\%), was used. Activity of the gamma source is approximately 300 kBq.

As a miniature gamma detector a semiconductor probe SDP310 / Z / 60 (S) Standart (manufactured by Baltic Scientific Instruments) was used. This gamma probe contains a quasi-hemispherical detector CdZnTe with a sensitive area of 50÷60 mm\(^2\), the energy resolution is less than 25 keV (~ 3.8\%) at 662 keV.

A set of polymethylmethacrylate (PMMA) plates with 1÷5 mm thickness was used as a phantom of human soft tissues. Point-like gamma source was placed between the plates at the increasing distances from the gamma probe. The probe was fixed on the top of the phantom, and the energy spectra were measured at different depths of gamma source.

![Figure 1. Scheme of an experimental setup.](attachment:image.png)
The scheme of the experiment is presented in the figure 1. Detector (CZT) is biased through a preamplifier with +350V from a high voltage power supply (HV). Signal from the detector preamplifier is shaped and amplified with a spectrometric amplifier (Amp), and then passed to the input of Lecroy WaveRunner oscilloscope, which can be used as a charge-to-digital converter (QDC/Scope).

Experimental energy spectra of $^{137}$Cs, obtained at the depths of 5, 15 and 25 mm of the source in PMMA phantom, are presented in the figure 2.

![Experimental energy spectra of $^{137}$Cs at 5, 15, 25 mm PMMA layer thickness between the source and the CZT gamma probe.](image)

In the presented spectra one can see photopeaks corresponding to emission lines of 32 keV (with a yield of 6%) and 662 keV (85% yield). The peak position in the spectra of these determines the energy of the gamma radiation. Area of the photopeak defines the intensity of radiation corresponding to the energy of 32 keV and 662 keV. Figure 2 shows that the intensity of 32 keV radiation line decreases faster than the intensity of 662 keV gamma line with immersion of gamma-ray source in the material. Dependence between the ratio of the photopeaks areas and the material layer thickness should be exponential according to the equation (2).

### 4. Experimental results

The ratio of the 32 keV and 662 keV photopeaks areas was measured for energy spectra of $^{137}$Cs at the distances of 5, 10, 15 and 20 mm between the source in the phantom and the gamma probe. Area of 32 keV photopeak was calculated with the correction for Compton contribution, by approximating the Compton continuum with a linear function around the photopeak. The experimental plot of the ratio of the 32 keV photopeak area to the one of 662 keV vs the PMMA layer thickness is presented in the figure 3.

Experimental data can be fitted with the linear equation as a first degree of a Taylor polynomial for an exponential function:

$$y(x) = kx + b,$$  \hspace{1cm} (3)
Coefficients $k$ and $b$ were calculated using the least squares method; $k = (-0.6 \pm 0.3) \times 10^{-2} \text{ mm}^{-1}$, $b = 3.6 \pm 0.2$.

The resulting linear dependence can serve as a first approximation for calibration of the gamma probe for determination of the depth of the compact gamma source positioning in soft tissues based on the detector's count rate in two energy discrimination windows.

![Figure 3. Ratio of 32 keV photopeak area to 662 keV photopeak area vs the thickness of PMMA layer.](image)

5. Conclusion
The feasibility study of the 3D compact gamma source localization method, based on the simultaneous registration of two emission lines of different energies, is presented within this work. Experiments with a point-like $^{137}$Cs gamma source placed inside a PMMA phantom and a room-temperature semiconductor gamma probe were carried out to obtain the dependence between the ratio of a 32 keV emission line intensity to the one of 662 keV and the PMMA layer thickness.

Experimental results showed that the dependence at first approximation can be fitted with a linear equation, which can be used for the detecting system calibration. However, a relatively low activity of the gamma source did not allow to determine the calibrating coefficients with the satisfactory accuracy.

Further objective of the study is to provide a set of experiments with a scintillation detector based on a LaBr$_3$:Ce crystal and a silicon photomultiplier to establish a possibility of 3D localization of malignant lesions with the current gamma-locator prototype.

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