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The Determination of the Total Efficiency for NaI(Tl) Detector by GATE Simulation

Nuray YAVUZKANAT[1*], Didem GÜNGÜR[2], Sezai YALÇIN[1]

[1]*Bitlis Eren University, Department of Physics, Bitlis*
[2]*Bitlis Eren University, Graduate School of Natural and Applied Sciences, Bitlis*
(ORCID: 0000-0001-5055-9185) (ORCID: 0000-0003-2742-1094) (ORCID: 0000-0001-6779-9230)

Abstract
In this study the total efficiency of the NaI(Tl) detector have been calculated by using Geant4 based GATE simulation program. The simulation was performed using point and disc isotropic gamma-ray sources at various distance between source and detector in the photon energy range 50-3000 keV. Results were compared with different analytical and Monte Carlo calculations obtained in the time of the periods 1958-2018. The calculated and simulated data indicated good agreement with finding more sensitive GATE simulation result in the lower energy range from 50 keV to 150 keV.

Keywords: NaI(Tl), Total Efficiency, Geant4, GATE.

NaI(Tl) Dedektörünün GATE Simülasyon Programıyla Toplam Veriminin Belirlenmesi

Öz
Bu çalışmada Geant4 tabanlı GATE simulasyon programı kullanılarak NaI(Tl) detektörünün toplam verimi hesaplanmıştır. Simulasyon, 50-3000 keV foton enerji aralığında çeşitli kaynak-detektör uzaklıklarında izotropik nokta ve disk gama ışını kaynağı kullanılarak gerçekleştirilmiştir. Sonuçlar, 1958-2018 periyodu boyunca elde edilen farklı analitik ve Monte Carlo hesaplamaları sonuçları ile karşılaştırılmıştır. Hesaplanan ve GATE simulasyonuyla elde edilen sonuçların birbiriyle uyumlu çıkmasının yanında, bu çalışmada 50 keV ile 150 keV arasındaki düşük enerjideki gamalar için çok daha hassas sonuçlar bulunmuştur.

Anahtar kelimeler: NaI(Tl), Toplam Verim, Geant4, GATE.

1. Introduction

Scintillation detectors are the main class of radiation detectors used in many areas (eg in high energy physics, nuclear physics, nuclear medicine, industry, security, geology, astrophysics, agriculture, radiation measurement of environmental samples, etc.) [1-4]. Hofstadter in 1948 firstly showed that thallium-activated sodium iodide crystals (NaI(Tl)) combining with PMTs (Photomultiplier Tubes) used as an efficient detector to measure gamma-rays and other ionizing radiations [5]. Therefore, NaI(Tl) is the first solid-state detector used as a gamma-ray spectrometer in the 50s and after that time it is still the most common gamma-ray detector system [6]. NaI(Tl) is a highly popular detector due to its good efficiency, wide operating temperature range, low consumption and low costs, as well as in-suit radioactivity measurements [7,8]. Today it is the most important part of nuclear medicine (used in mammography, gamma cameras, and positron emission tomography) as well as astrophysics. The NaI (T1) detectors are also used in the measurement of the environmental radioactivity in the marine as used in the Fukushima nuclear accident [9].

[*]Sorumlu yazar: nyavuzkanat@beu.edu.tr
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The most important properties of the radiation detector are the detector response function, the total efficiency (TE), the full energy peak efficiency (FEPE) and the detector resolution. It is necessary to determine the detector properties to make gamma- ray measurements over a wide energy range. In the gamma-ray activity measurement, there are two critical properties in detector efficiency; total efficiency and full energy peak energy efficiency. To measure the absolute activities from the gamma-ray source over a wide energy range, the total efficiency needs to be known. The total efficiency is described by four different methods as experimental, empirical, analytical and Monte Carlo approach [10]. It is necessary to use standard sources to determine the total efficiency in the experimental method. These standard sources are quite expensive and require time to prepare in the laboratory [11]. It is also difficult to find standard gamma sources in the desirable energy range. Instead of the determination of the total detector efficiency by the experimental method, it is easy to fit the measurement values by analytical function or use the computer program based on the gamma-rays interactions with the detector [12]. One of the important analytical methods calculates the efficiency via identifying the average chord length which is called Mean Chord Length (MLC) [13,14]. In addition to experimental and computer-based calculations, new published analytical studies are directly calculated the detector efficiency for various detector-source arrangements [10,15-17].

Monte Carlo (MC) simulation method, used in many fields from the medical physics to particle physics and keeps its popularity. Nowadays it is widely used to calculate the application parameters such as the activity measurement, the detector efficiency, coincidence summing corrective factor in gamma-ray spectroscopy. Well-known multi-purpose MC codes are PENELOPE, MCNP, Geant4, GATE, FLUKA, EGS, etc. [18].

GATE is an advanced open- source software developed by international collaborations and dedicated to the medical applications and radiotherapy. Recently it plays a key role in terms of designing new medical devices, acquisition protocols, quality control systems of the medical imaging devices and image reconstructions. It is also used in the characterization of the detector system which is the most important part of the positron emission tomography (PET), etc. GATE runs with Geant4 simulation toolkit which is the validated physics models, complex geometrical volume description and powerful 3D visualization (such as Qt mode) [8, 19-23].

In this study, the total efficiency of the NaI(Tl) detector was obtained using the Geant4 based GATE simulation program. The simulation code was modeled for 3”x3” and 2”x2” cylindrical NaI(Tl) detector systems and obtained the output as a root file for every gamma-ray energy from 50 keV to 3000 keV. A simulated energy spectrum was used to calculate the total efficiency of the detector and compared the result with published results by using analytical and MC calculations. Founded the total efficiency values with GATE simulation were found to agree with the literature.

2. Material and Method

Modeled GATE (Geant4 Application for Tomographic Emission) Simulation

We simulated the photon detection efficiency of the NaI(Tl) detector with Geant4 based GATE simulation program. The simulation was performed using the different shapes of the sources at various distances (between source and detector) in the photon energy range 50-3000 keV. The versions of the GATE and Geant4 were 8.0 and 10.3 respectively. Firstly, a cylindrical NaI(Tl) detector was defined as a three-inch length and three-inch diameter. The point source was positioned at 0.001, 0.5 and 10 cm distance from the detector surface. The disc source was also determined in the simulation with a radius of 3.18 cm and located at 3 and 10 cm away from the detector surface. Moreover, 2”x2” NaI(Tl) detector was also defined in the simulation and calculated the total efficiencies of the detector for 0.001, 5 and 10 cm detector-source distance to compare the result with the current publication. Simulation setup and disc source visualization in Geant4 is shown in Figure 1.

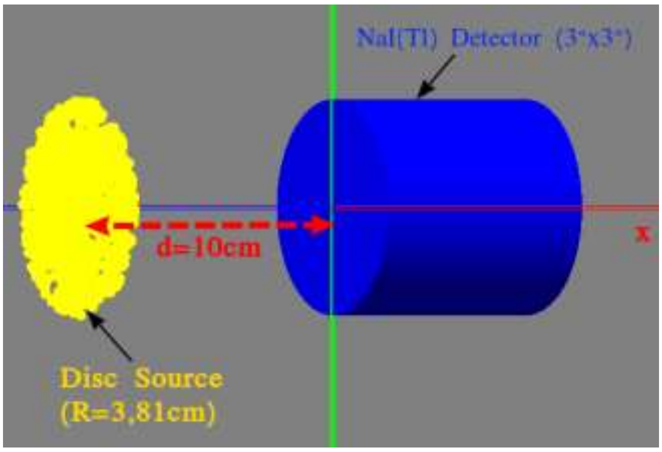


Figure 1. Geant4 visualization of the simulation setup for detecting gamma-rays emitting from disc source. Blue cylinder volume was defined for NaI(Tl) scintillation material with the size of 3"x3". Yellow points represent the disc source with radius of R=3.81 cm

In Figure 2, gamma-rays irradiated from the disc source located at 10 cm distance from the detector. Short red lines represent the travel distance of the electron that occurs after the interaction between scintillation and gamma-rays. Green long lines classically represent the photons in the Geant4.

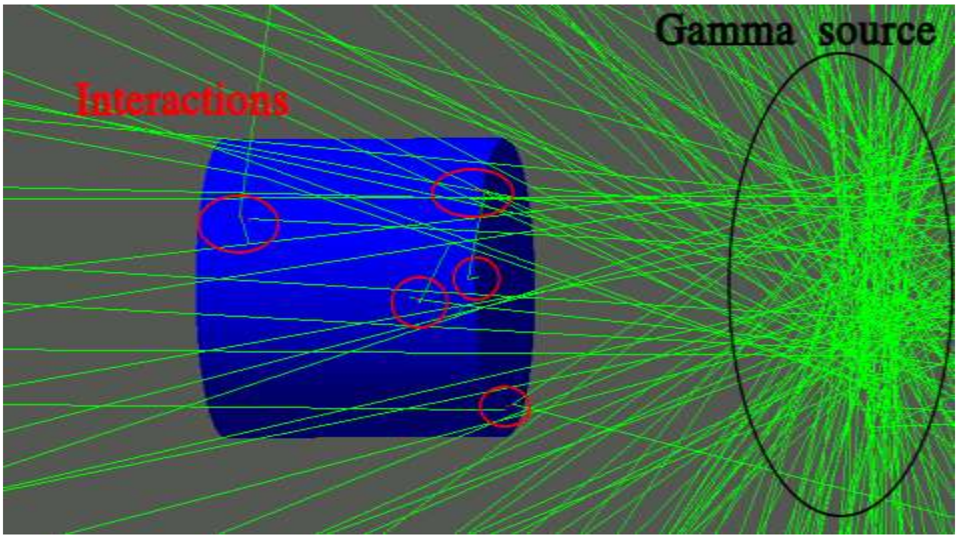


Figure 2. Green lines which is coming from the disc source (showing with black circle in the fig.) represent gamma rays in Geant4 simulation. Red circles in the figure show the interactions between scintillation and gamma-rays. Red lines indicate the electrons in the Geant4 simulation. In the simulation, detector volume was also capsuled with thin aluminum layer

Secondly, the physics list was chosen according to the photons energy range, therefore the physics-list builder name was called emstandard (electromagnetic physics-list) provided by the Geant4. After defining the system, source, digitization, and readout parameters, lastly, we described the data output as a root file that give all functionalities to achieve big data processing, numerical analysis and storage [30]. All occurred data outputs in the simulation were analyzed by ROOT software. The energy spectrum was obtained from the GATE simulation by recording all the interactions and the deposit energy of the detector crystal. Total efficiencies were calculated using the following equation:

$$TotalEfficiency = \frac{N_D}{N} \tag{1}$$

where N_D is the number of the detected photons by the scintillation, and N represents the number of photons emitted by the source. The net count of the emitted photons was stabilized with one million gamma-rays for each different case in the simulation. Detected photon number was found from the energy spectrum and all results were listed in the Table 1 and Table 2.

3. Result and Discussion

The total gamma efficiencies of the NaI(Tl) detector for the disk and point sources were evaluated at a different detector-source distances in the various energy ranges from 50 keV to 3000 keV. The total photon efficiencies for the disk and point sources obtained from the GATE simulation were compared with the calculated efficiencies by various analytical Monte Carlo approaches over the time period (between 1958 and 2018). In Table 1, there is a comparison between simulation with GATE and analytical calculations for NaI(Tl) detector's photon efficiency. In that part of the simulation, the disc source radius was defined as a 3.81 cm and located at two different positions (3 and 10 cm away from the detector surface). The analytical calculations and simulation results showed in good agreement. Especially, present work results consistent with the hybrid Monte Carlo method results calculated by [3]. Figure 3 shows that comparison between this work with different analytical methods and Monte Carlo techniques in terms of the total photon efficiencies for NaI(Tl) scintillator in the energy range between 50 keV and 3000 keV. In the Figure 3 (b) there is a slight discrepancy over the 1332 keV between this work and others (exception of the [3] and [27] works).

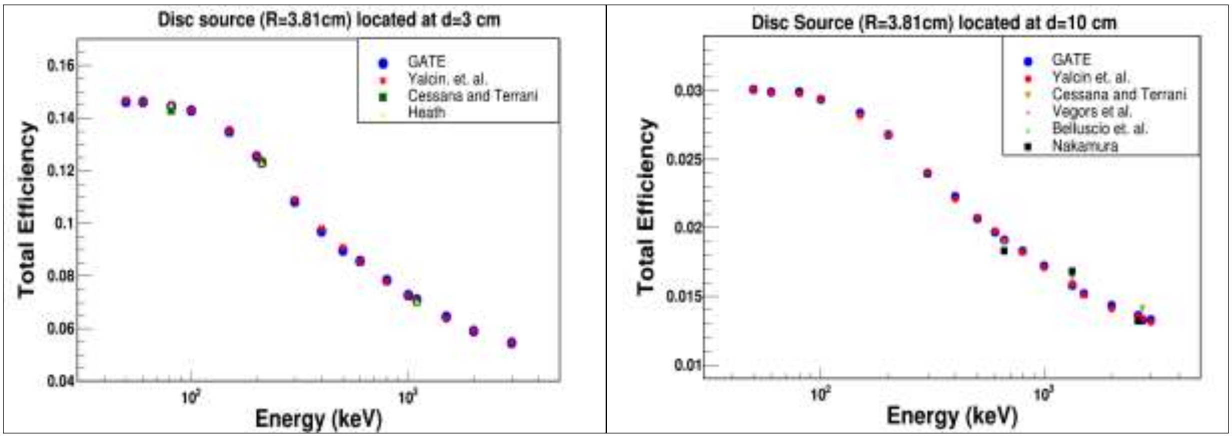
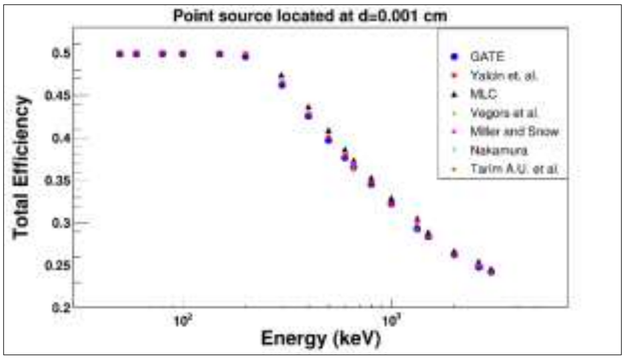
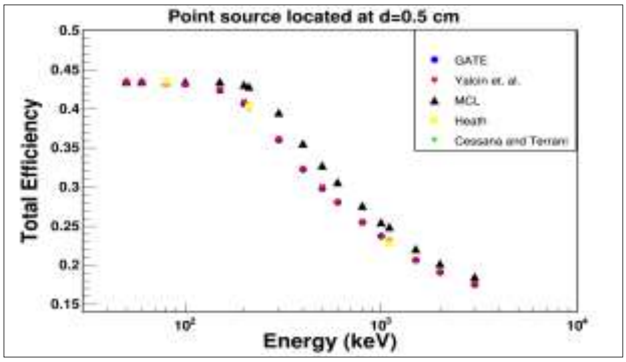


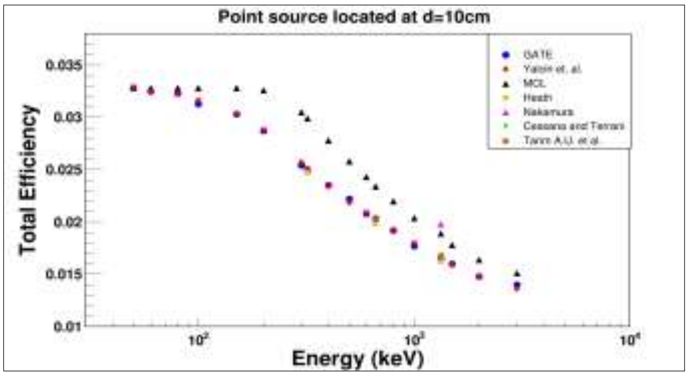
Figure 3. Total photon efficiency for a 3"x3" NaI(Tl) scintillator with a 3.18 cm radius disc source positioned at (a) 3 cm and (b) 10 cm distance between source and the detector surface

In Table 2, Geant4 based GATE simulation result for point source is compared with an analytical and different types of Monte Carlo calculations in total photon efficiency of the NaI(Tl) detector. The point source was positioned at three different places with 0.001, 0.5 and 10 cm away from the detector. The analytical calculation (except Mean Chord Length) and different types of Monte Carlo calculations consistent with GATE simulation results. Figure 4 also indicates that the comparison between this study and different analytical methods or Monte Carlo techniques. In the Figure 4 (a), (b) and (c), the divergence between MCL method results and other values rises from the position of 0.001cm to 10 cm. It is obvious that present work with obtained GATE simulation in the lower energies is having more precisely calculation than other studies, because their values are identical until the 200 keV energy. It is clearly seen in Figure 3 and Figure 4 that the total photon efficiency decreases with increasing the distance between the detector and the source. It causes most likely changing the solid angle by reducing the detector source distance, therefore, more photons interact with the scintillation.





(a) (b)



(c)

Figure 4. Total efficiency for a 3"x3" NaI(Tl) scintillator with a point source positioned at **(a)** 0.001 cm **(b)** 0.5 cm and **(c)** 10 cm distance between source and the detector surface

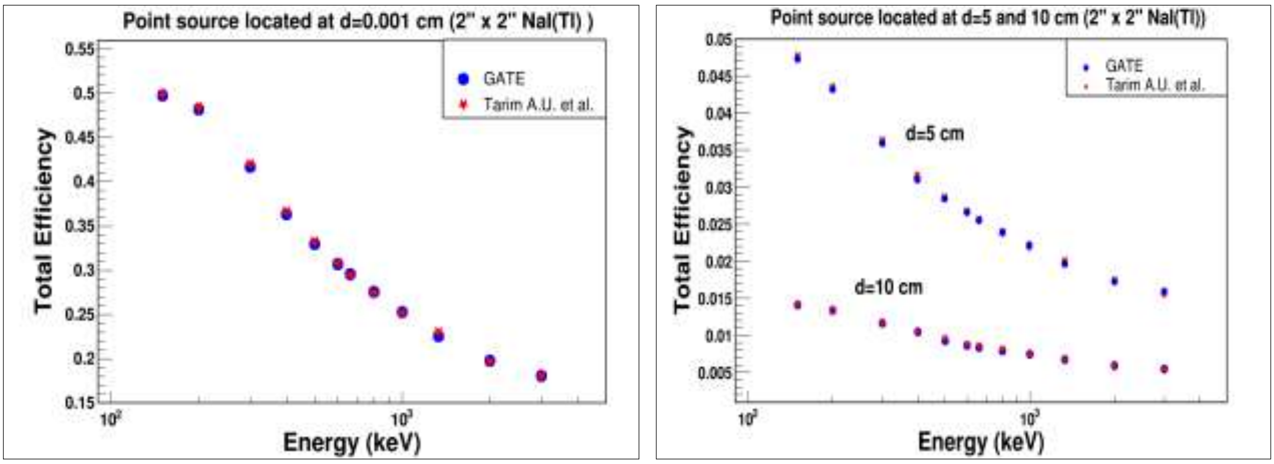
Table 1. Total counting efficiency values for a 3" x 3" NaI(Tl) detector with disc source (R=3.81 cm) located at d=3 and 10 cm

Energy (keV)	Total Efficiency									
	Present Work		Yalcin et al.[3]		Cessana A. and Terrani M.[24]		Nakamura T. [25]	Belluscio et al. [26]	Heath R.L. [28]	Vegors et al.[27]
	3	10	3	10	3	10	10	10	3	10
50	0.1462	0.0301	0.1466	0.0301	-	-	-	-	-	-
60	0.1462	0.0299	0.1462	0.0299	-	-	-	-	-	-
80	-	0.0299	-	0.0298	-	-	-	-	-	-
81	0.1445	-	0.1448	-	0.143	-	-	-	0.145	-
100	0.1429	0.0294	0.1428	0.0294	-	-	-	-	-	-
150	0.1348	0.0284	0.1352	0.0282	-	-	-	-	-	-
200	0.1255	0.0268	0.1257	0.0268	-	-	-	-	-	-
212	0.1231	-	0.1236	-	0.123	-	-	-	0.123	-
300	0.1084	0.024	0.1090	0.0241	-	-	-	-	-	-
400	0.0971	0.0223	0.0979	0.0221	-	-	-	-	-	-
500	0.0898	0.0207	0.0908	0.0208	-	-	-	-	-	-
600	0.0857	0.0197	0.0855	0.0198	-	-	-	-	-	-
661	-	0.0191	-	0.0191	-	0.0191	0.0183	0.019	-	-
800	0.0784	0.0183	0.078	0.0182	-	-	-	-	-	-
1000	0.0728	0.0172	0.0726	0.0171	-	-	-	-	-	-
1100	0.0711	-	0.0711	-	0.0701	-	-	-	0.0702	-
1332	-	0.0158	-	0.0159	-	0.0164	0.0168	0.0164	-	0.0156
1500	0.0646	0.0152	0.0639	0.0151	-	-	-	-	-	-
2000	0.0591	0.0143	0.0591	0.0141	-	-	-	-	-	-
2620	-	0.0136	-	0.0135	-	-	0.0132	-	-	0.0133
2750	-	0.0133	-	0.0134	-	0.0141	-	0.0141	-	-
3000	0.0546	0.0133	0.0546	0.0131	-	-	-		-	-

Table 2. Total counting efficiency values for a 3" x 3" NaI(Tl) detector with point source located at d=0.001, 0.5 and 10 cm

Energy (keV)	Total Efficiency																			
	Present Work			Özmutlu C. and Ortaovalı A.Z. [13]			Yalcin et al.[3]			Tarım A.U. et al. [4]		Nakamura T. [25]		Cessana A. and Terrani M.[24]		Heath R.L. [28]		Belluscio et al. [26]	Miller and Snow[29]	Vegors et al.[27]
	0.001	0.5	10	0.001	0.5	10	0.001	0.5	10	0.001	10	0.001	10	0.5	10	0.5	10	10	0.001	0.001
50	0.4990	0.4347	0.0328	0.4999	0.4349	0.0328	-	-	-			-	-	-	-	-	-	-	-	-
60	0.4990	0.4345	0.0325	0.4999	0.4349	0.0328	-	-	-			-	-	-	-	-	-	-	-	-
80	0.4992	0.4335	0.0323	0.4999	0.4349	0.0328	-	0.4333	-			-	-	0.435	-	0.435	-	-	-	-
100	0.4995	0.4318	0.0313	0.4999	0.4349	0.0328	-	-	-			-	-	-	-	-	-	-	-	-
150	0.4991	0.4240	0.0303	0.4999	0.4349	0.0328	-	-	-			-	-	-	-	-	-	-	-	-
200	0.4957	0.4068	0.0287	0.4984	0.4312	0.0326	-	-	-			-	-	-	-	-	-	-	-	-
212	-	0.4022	-	-	0.4289	-	-	0.4013				-	-	0.404	-	0.403	-	-	-	-
300	0.4625	0.3601	0.0254	0.4732	0.3954	0.0305	-	-	-			-	-	-	-	-	-	-	-	-
320	-	-	0.0249	-	-	0.0299	-	-	0.0249			-	-	-	0.0251	-	0.0247	0.025	-	-
400	0.4257	0.3226	0.0235	0.4374	0.3557	0.0278	-	-	-			-	-	-	-	-	-	-	-	-
500	0.3975	0.2980	0.0222	0.4095	0.3277	0.0258	-	-	-			-	-	-	-	-	-	-	-	-
600	0.3770	0.2808	0.0208	0.387	0.3063	0.0243	-	-	-			-	-	-	-	-	-	-	-	-
661	0.3660	-	-	0.3741	-	-	0.3646	-	-	0.3652	0.0202	0.367	-	-	-	-	-	-	0.370	0.362
662	-	-	0.0203	-	-	0.0234	-	-	0.0202			-	0.0183	-	0.0201	-	0.0198	0.019	-	-
800	0.3453	0.2546	0.0192	0.3537	0.276	0.022	-	-	-			-	-	-	-	-	-	-	-	-
1000	0.3227	0.2376	0.0177	0.3298	0.255	0.0204	-	-	-			-	-	-	-	-	-	-	-	-
1100	-	0.2292	-	-	0.249	-	-	0.2281	-			-	-	0.229	-	0.228	-	-	-	-
1330	-	-	0.0165	-	-	0.0189	-	-	0.0164			-	0.0168		0.0165		0.0162	0.0164	-	-
1332	0.2929	-	-	0.3057	-	-	0.2930	-	-	0.2990	0.0168	0.296	-	-	-	-	-	-	0.302	0.293
1500	0.2841	0.2066	0.0160	0.2895	0.2208	0.0178	-	-	-			-	-	-	-	-	-	-	-	-
2000	0.2628	0.1910	0.0148	0.2671	0.2023	0.0164	-	-	-			-	-	-	-	-	-	-	-	-
2620	0.2478	-	-	0.255	-	-	0.2476	-	0.0140			0.249	-	-	-	-	-	-	0.250	0.248
3000	0.2424	0.1755	0.0140	0.2464	0.1855	0.0151	-	-	-			-	-	-	-	-	-	-	-	-

In figure 5 there is a comparison between recently published efficiency values obtained from a simple computational Monte Carlo algorithm (developed by Tarım et. al.) and Geant4 based GATE simulation results. In this part of the simulation 2”x2” cylindrical NaI(Tl) detector system was defined and three different source-detector distance was used (0.001, 5 and 10 cm). It is clearly seen that the calculated and simulated values of the efficiencies for NaI(Tl) detector indicated good agreement.



(a) **(b)**

Figure 5. Total efficiency for a 2"x2" NaI(Tl) scintillation detector with a point source positioned at **(a)** 0.001 cm **(b)** 5 cm and 10 cm distance between source and the detector surface

4. Conclusion

In this study, the total efficiency of the cylindrical NaI(Tl) (3" x 3") and (2" x 2") detectors have been calculated for isotropic point and disc gamma-rays source by using Geant4 based GATE simulation program. To compare our results with other different analytical and Monte Carlo calculation results we have evaluated the efficiencies in the photon energy range 50-3000 keV and for 0.001 cm, 3 cm, 5 cm and 10 cm distance between the source and the detector. The results are shown in table 1, table 2 and figures the agreement is quite good in the whole energy range. However, we can say that Geant4 gives more sensitive results in the low energetic photon (between 50 and 200 keV).

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