OPTIMIZATION OF THE BCA FACILITY USING THE γ SHIELD AND IMPROVEMENT OF ACCURACY USING ORNL ANTHROPOMORPHIC PHANTOMS

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Reducing the patient dose in BCA facility

OPTIMIZATION OF THE BCA FACILITY USING THE $\gamma$ SHIELD AND IMPROVEMENT OF ACCURACY USING ORNL ANTHROPOMORPHIC PHANTOMS

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The analysis of body elements using the prompt-γ rays neutron activation method is a very useful and highly accurate method¹ that has many applications in different fields such as the diagnosis of specific diseases including certain types of cancers. To prevent patients from γ-rays produced by the system, an efficient strategy is to apply a γ-shield. In this study, the γ-shield was embedded in three separate positions. The influence of these positions on reducing the effective dose was examined in a 5-year-old Oak Ridge National Laboratory (ORNL) mathematical phantom. Other considered parameters were sensitivity and coefficient of variation (CV) of thermal neutron flux.

With the best configuration, the total effective dose per minute (Eₜ) was decreased about 52.48% and the sensitivity were about 1.94 fold higher than when no shield was present, respectively.

INTRODUCTION

Body Composition Analysis (BCA) by in vivo elemental measurement has been of considerable value to clinicians over sixty years. Most of the works in this field has been performed by the prompt γ-rays in vivo neutron activation analysis (IVNAA) technique due to its "gold standard" in determining certain chemical elements of the body². IVNAA facilities have contributed a significant amount of knowledge in the study of diseases, such as osteoporosis, obesity, AIDS, cancer, anorexia, renal disorders, and aging³. This non-destructive technique is the gold standard method for determining total body nitrogen (TBN), and is one of the most precise ways to measure other essential body elements such as hydrogen, carbon and calcium². In this method, the patient has no alternative except to be exposed to by doses resulting from rays’ collision. However, one of the major challenges of the prompt γ-ray IVNAA method is the low dose of radiations that the patient receives, which thereby protects the patient from overexposure, preventing from experiencing the side effects associated with exposure to this ionizing radiation. Therefore, the received dose from non-essential beam such as undesirable γ rays must be reduced. The most prominent sources of undesirable γ-rays are primary gamma rays emitted from neutron sources and a secondary γ rays produced from neutron collision with components of the IVNAA system. During the last sixty years passed from the application of this technique, this subject was generally taken into consideration by other researchers such as McNeill et al.⁴, Ryde⁵, Krishnan⁶, Borovnicar⁷, Estamatelatos et al.⁹. In 2007, the Neutron Activation Research Centre (NARC) of Ferdowsi University of Mashhad (FUM), designed an
appropriate γ-shield for neutron sources, such as $^{241}$Am-Be and $^{252}$Cf, and then applied it to the prompt-γ rays IVNAA facility\cite{10,11}. Here, the studies were performed on the IVNAA facility with bilateral irradiation that was optimized by NARC in 2010, considering having uniformity of activation rate distribution in the body \cite{2}.

MATERIALS AND METHODS

Facility description

The prompt-γ IVNAA facility represented in Figure 1 is the optimized system from NARC, which has uniformity of activation rate distribution in the body\cite{2} and it was originally designed at the Monash Medical Center (MMC)\cite{7}.

In this facility, there is an orthogonal parallelepiped void cast collimator made of graphite on the top and bottom of the phantom surrounded by concrete, which serves as a neutron and γ shield. Four $^{241}$Am-Be neutron sources are located inside the collimator (one pair on top, the other on the bottom). Two pre-moderators made of 1 cm thick polyethylene are positioned on both sides of the phantom.

Two pairs of NaI(Tl) detectors with a borated paraffin wax cover are bilaterally positioned to the phantom.

To protect the detectors from undesirable γ rays, lead layers of 5 cm in thickness are located on the top and bottom of them. Finally, to increase thermal neutron flux in the phantom, polyethylene and Graphite layers are bilaterally placed to serves as pre-moderator and reflector, respectively.

Two major sources of undesirable γ rays are the γ rays emitted from $^{241}$Am-Be neutron sources and those are produced from neutrons collisions with the facility components. In a previous study, the shielding effects on gamma flux and the gamma radiation spectrum through a cubic water phantom were examined. Six elements with a high attenuation coefficient, ranged in the thickness from 0.5 to 6 cm, were selected and placed in two separate positions: around the source and around the patient. By taking into consideration the goals of decreasing undesirable gamma flux and increasing facility sensitivity, the best setup was determined which were 5.6 cm thick layer of bismuth and tungsten around the patient and 6 cm thick W layer and Bi layer around the neutron sources\cite{12}. In the present paper, another case was also considered in addition to the study that garnered the optimal results previously described. Therefore, three positions of the γ shield are: 1) the top and bottom of the phantom before the pre-moderators (with 5.6 cm thick bismuth and tungsten), 2) around the sources (with a 6 cm radius of bismuth, tungsten), 3) around the sources and the collimators walls (with 3 cm thick of bismuth).

Since the dose received by patients, and especially by children must be calculated with high accuracy, we used mathematical anthropomorphic phantoms designed by the Oak Ridge National Laboratory (ORNL) representing 5-year-old children. This replacement caused a fundamental reduction in error in total body dose estimation compared to rectangular water phantoms; and also allowed the absorbed radiation dose to be separately calculated in different organs.
Important parameters

For dosemetry in IVNAA facility, the dose deposition in separate organs and effective dose for whole body should be evaluated. According to ICRP publication 103, the effective dose is the sum of the equivalent dose, which itself is defined as weighted absorbed dose with radiation weighting factors ($w_R$), in all organs and tissues weighted by tissue weighting factors ($w_t$)\(^{(13)}\). In external exposure, the relative biological effectiveness for neutrons is reflected by their $w_R$ and is intensely dependent on their energy at incident on the body. For calculating the equivalent dose, the radiation weighting factors ($w_R$) must be determined with high accuracy. It is essential to specify the exact energy of incident neutron on the body. On the other hand, the presence of the moderators and reflectors in IVNAA facility leads to a change in the energy spectrum of neutron emitted from the source and thereby the energy of them is unspecified at incident on the body. It is possible to calculate the equivalent dose with a method called secondary sources. However, it must be accompanied with relatively complicated and long calculations. Instead, the effective dose can be obtained the same as its exact value in a good approximation by substituting the equivalent dose with the organ dose equivalent. This was examined in real systems such as IVNAA facility in a comprehensive study in NURC and has been verified\(^{(14)}\). According to the definition by NCRP committee in 2002, the organ dose equivalent ($\overline{H}_i$) is determined as an average of dose equivalent ($H$) over all points in the organ or tissue\(^{(15)}\). The dose equivalent ($H$) is defined at a point in tissue and can be directly measured\(^{(15)}\). $H$ is given by:

$$H_i = \int Q(L)D(L)dL$$  \hspace{1cm} (1)

where $Q(L)$ is the quality factor for particles as a function of linear energy transfer ($L$) and $D(L)$ is the spectral distribution in terms of $L$ of the absorbed dose at the point ($D$). Therefore, $\overline{H}_i$ is given by:

$$\overline{H}_i = M_t^{-1}\int\int Q(L)D(L)\rho(x)\ dLdx$$  \hspace{1cm} (2)

where there is a second integration over the points $x$ in tissue $t$ with tissue density $\rho(x)$ and total mass $M_t$. By substituting the organ dose equivalent for the equivalent dose, the effective dose ($E$) can be defined as the sum of the weighted organ dose equivalents with tissue weighting factors in all tissues and organs of the body with an acceptable approximation\(^{(15)}\):

$$E = \sum w_i H_i \approx \sum w_i \overline{H}_i$$  \hspace{1cm} (3)

The total dose received by the body ($E_T$), as an important quantity that can give confidence to reduce risk, in addition to the dose received per one neutron (particle) emitted from the source ($E_n$), is proportional to exposure time ($T_{exp}$) and source activity ($Act$), i.e.,

$$E_T = E_n \times T_{exp} \times Act$$  \hspace{1cm} (4)

Besides, the exposure time is inversely proportional to the neutron activation rate (which itself depends on thermal neutron flux) and activity of the neutron source ($T_{exp} \propto (\varphi_{th} \cdot Act)^{-1}$)\(^{(16)}\). Thus, there is a possibility to reduce the dose received per one neutron using the $\gamma$ shield, but the total dose increases due to the increased duration of irradiation as a consequence of decreasing neutron flux. Therefore, in addition to $E_n$, it is necessary to introduce a quantity as...
an indicator of total received dose, including the exposure time. For this, the ratio of thermal neutron flux to effective dose per one neutron emitted from the source was defined as device sensitivity and the total dose is inversely proportional to it:

\[ E_t \propto \left( \frac{\phi_{\text{th}}}{E_n} \right)^{-1} \]  

(5)

Where \( E \) is effective dose received per one neutron and \( \phi_{\text{th}} \) is thermal neutron flux over the phantom. According to equation 5, the total dose decreases as the facility sensitivity increases.

It should be noted that in the facility for whole body IVNAA, uniformity of neutron activation rate or \( \gamma \) production rate are of great importance in accuracy measurement\(^{(16)}\). Therefore, applying any changes to the system like shielding, which causes modification of thermal neutron flux, may affect uniformity of neutron activation rate.

To determine the uniformity of some dataset distribution like thermal neutron flux, we calculated the coefficient of variation (CV) of this dataset with the following equation:

\[ CV = \frac{\sigma}{\bar{X}} \]  

(6)

where \( \sigma \) and \( \bar{X} \) are the standard deviation and arithmetic mean, respectively.

**Monte Carlo simulation**

The Monte Carlo simulation of the IVNAA facility was performed using MCNP-4C code\(^{(17)}\) and calculations were done by computers with an Intel® Core™ i7 CPU 64-bit operating system.

The \( ^{241} \text{Am-Be} \) source emits \( \gamma \)-rays in addition to neutrons, thereby having both a neutron and \( \gamma \) energy spectrum. Since it is impossible to define two sources concurrently, there needs to be two separate programs for any energy spectrum. The \( ^{241} \text{Am-Be} \) neutron energy spectrum was selected from the International Atomic Energy Agency (IAEA) 403 report\(^{(18)}\), and the \( \gamma \) energy spectrum is one that measured in Neutron Activation Research Centre (NARC) of Ferdowsi University of Mashhad (FUM)\(^{(19)}\). The F4 and F6 tallies were used for thermal neutron flux and dosemetry calculations, assuming Kerma approximation, respectively\(^{(17)}\).

Since neutron and \( \gamma \) doses due to neutron source as well as \( \gamma \) dose due to the \( \gamma \) source are calculated separately, we could compare them to each other. It should be noted that for the \( ^{241} \text{Am-Be} \) source, the ratio of \( \gamma \) per neutron emission is 0.596\(^{(20)}\). Thus, the values obtained from the \( \gamma \) source must be multiplied to this correction factor.

The neutron quality factors were chosen from the NCRP 38 report\(^{(21)}\). Since the quality factors for \( \gamma \) are equal to one at any energy level, the total absorbed dose due to \( \gamma \) and its dose equivalent are the same. Furthermore, the tissue weighting factors were selected from ICRP 103 report\(^{(13)}\). Measurements were examined for the 5-year-old ORNL phantom\(^{(22)}\). In total, 33 programs were run in 264 hours to achieve statistical error of order of about 2%.

**Results and discussion**

**Dose calculation**
Figure 2 represents the total organ dose equivalent values, $H_i$, per minute calculated on main body organs in the presence or absence of a $\gamma$ shield. The activity of $^{241}$Am-Be source is $10^7$ n/s.

The quantity of $H_i$ for the brain, uterus, gall bladder, pancreas, small intestine, colon, and esophagus were similar to each other. Likewise, the stomach, spleen, heart, bladder, liver, and ovaries received similar quantities of $H_i$. In addition, the total organ dose equivalent in the thyroid was very close to that of the bone marrow.

In all cases (with or without the shield), the maximum organ dose equivalent was related to the skin, breasts and testes; while, the adrenals and kidneys received the minimum.

The remainder organ includes adrenals, gall bladder, heart, kidneys, muscle, pancreas, small intestine, spleen, thymus, and uterus$^{(13)}$. The organ dose equivalent had a considerable value in all of them except the adrenals, and kidneys. The organ dose equivalent for remainder organ was obtained from the arithmetic mean of them. Calculations showed that the organ dose equivalent of the remainder organ for males and females were somewhat the same.

Generally, using a $\gamma$ shield in IVNAA facility caused a $\gamma$ dose decrease in all organs. As shown in Figure 2, using tungsten caused a greater decrease in $\gamma$ radiation than bismuth and maximum reduction achieved when tungsten was placed on the top and bottom of the patient. We consider the reduction of organ dose equivalent in lungs, gonads, bone marrow, and bones because they are more important than other organs, (e.g. cancers related to them are most common). The percentages of reduction of organ dose equivalent are shown in Table 1.

The values of total effective dose in one minute ($E_T$) are shown in Figure 3. Generally, it can be concluded that in reducing effective dose, treatment with tungsten is better than treatment with bismuth. The effective dose in the absence of a $\gamma$ shield is $1.72\times10^{-2}$ mSv/min. The greatest decreasing was seen with tungsten at the top and bottom of the phantom (66.21%), and around the sources (53.76%). It should be noted that, covering the inner collimators walls with a 3cm thick bismuth layer when neutron sources were surrounded by a 6cm thick layer of tungsten or bismuth does not make much difference.

The incident dose by patient in the IVNAA facility is due to three sources: emitted neutron from $^{241}$Am-Be sources, $\gamma$ rays emitted by $^{241}$Am-Be sources and $\gamma$ rays produced by neutron interactions with facility components, (called secondary $\gamma$ rays). To study the contribution of each of them on the total effective dose, the $E$ values due to each of the aforementioned sources were separately plotted in Figure 3. The greatest contribution to the dose received by the body was related to neutrons followed by secondary $\gamma$ rays, and $\gamma$ rays emitted from sources contributed the least to the effective dose. Using the $\gamma$ shield, the reduction of the effective dose due to neutrons is almost similar to the total effective dose. Specifically, the effective dose due to $\gamma$ rays from $^{241}$Am-Be source decreased about 92%; while the shield had a much less effect on secondary $\gamma$ rays.

We were interested in comparing our calculated dose data with some others experiments. Borovnicar et al., Beddoe et al., Nydegger et al., and Haas et al. have measured the total body nitrogen (TBN) or/and total body chlorine (TBCl) with similar IVNAA facilities$^{(7,8,23-25)}$. Table 2 shows the effective whole body radiation dose in their experiments and our calculated effective dose in the absence of shield. There is a good agreement between their measurements and our results. Furthermore, the effective dose due to only $\gamma$ rays was...
compared with Miri et al. work in table 3\textsuperscript{(11)}. Despite having differences between their setup and our facility, the evaluated data have a good agreement with each other.

**Determinant parameters**

As previously noted, thermal neutron flux is one of the considerable parameters in the IVNAA method, because any prominent change at its spectrum can affects uniformity in neutron activation rate and total effective dose due to an increasing duration of irradiation. In this paper, thermal neutron flux was calculated on the whole body phantom and its organs to obtain facility sensitivity and CV parameters, respectively. Figure 4 depicts thermal neutron flux in various cases, with and without the shield. When the shields surrounded the sources, the thermal neutron flux on the body was increased. These elements reduced the energy of the neutrons from the sources through \((n,xn)\) interactions, where \(x\) can be 2 or 3 depending on neutron energy. These low-energy neutrons become thermal through the interaction with pre-moderators and water in the body. On the contrary, placing these elements near the phantom such as on the top and bottom of pre-moderators caused a reduction in thermal neutron flux. This is due to the following results: First, the energy of the neutrons from source was decreased through interaction with elements in the facility such as graphite (as collimator). Second, further reduction of the energy occurred through the interaction (a type of \((n,xn)\)) with gamma shield, located after graphite. Finally, these neutrons were mainly absorbed by polyethylene (pre-moderator) and did not reach to the phantom (see fig.1). In this case, tungsten was one undesirable situation, which caused a reduction in thermal neutron flux of about 53.18\% whereas the maximum percent of variability in other cases was below 16\%. The thermal neutron flux decreased through covering the inner collimator walls by bismuth with the same reason.

The quantities of sensitivity are represented in Figure 5. Generally, the sensitivity increased in the presence of the \(\gamma\) shield. The best system configuration with the highest sensitivity was obtained when a 6 cm thick tungsten layer covered the neutron sources. The sensitivity increased about 2.52-fold than when no shield was present. Adding 3cm thick of bismuth covered the inner collimator walls to the shield around the sources led to reduce the sensitivity because of its influence in reduction of thermal neutron flux.

The quantities of CV parameters are shown in Figure 6. As seen in this figure, CV values for all cases were changed from 18 to 21\%. Tungsten placed around the sources, together with a 3 cm thick layer of bismuth covering the inner collimator walls, produced the lowest CV and consequently, the best uniformity of activation rate distribution. As previously noted, the studied facility in this paper was optimized with a uniformity of activation rate\textsuperscript{(2,13)}. For calculating the activation rate uniformity, the distribution of thermal neutron flux was usually determined in a set of lattices with small dimensions throughout the body. In a similar IVNAA setup where a latticed 5-year-old ORNL phantom was used, the CV of thermal neutron flux distribution in the whole body was found to be approximately 19\%. However, our calculated CV parameters had suitable accuracy and good agreement with this result despite the fact that they are related to thermal neutron flux distribution in body organs.

To show the shielding effect on changes on thermal neutron distribution in the body, the difference between any of them and free shielding setup or the shield producing lowest CV
were listed in Table 4. According to this Table, among these shields, only one led to a decrease in CV that was tungsten around the sources in addition to bismuth covered inner collimator walls. Additionally, it can be concluded that the CV index in a configuration created the highest sensitivity, which means the system with tungsten around the sources, has been increased about 7.06% and 11.03% in comparison with the free shield and the lowest CV case, respectively.

To select the best situation for setting the γ shield in IVNAA facility, all of the studied parameters must be taken into consideration. A 6cm thick tungsten layer on the top and bottom of the patient (Wₜ&ₘ₉) can be chosen just regarding to dose reduction due to the greatest decrease (66.21%) in the value of effective dose in the presence of it. However, this can also reduce thermal neutron flux about 53.18% compared to no shielding. Respecting sensitivity, the greatest sensitivity (2.51 fold higher) occurred with a 6 cm thick tungsten layer around the ²⁴¹Am-Be sources (Wₜ) which also reduced the effective dose by about 53.76%. When a 3cm layer of bismuth covered the inner collimator walls and a 6cm thick layer of tungsten surrounded neutron sources (Wₜ+Biₖ), the sensitivity increased about 1.94 fold and the effective dose decreased by about 52.48% compared to cases where shield was present. Since there was not much difference between the latter case and Wₜ in effective dose reduction, this is a second alternative for high sensitivity. Moreover, the Wₜ+Biₖ produced best uniformity of neutron activation rate, or in other words, the lowest CV in thermal neutron distribution in the whole body. Therefore, considering all of the parameters, Wₜ+Biₖ may be the best situation for setting the γ shield in an IVNAA facility.

Conclusions

This paper tried to optimize the IVNAA facility with the goal of decreasing the total effective dose with no significant change on thermal neutron flux and its distribution. To this end, γ shields were designed to prevent the patient from being overexposed to radiation. For accurate dose assessment, the orthogonal water phantom was replaced with an anthropometric 5-year-old ORNL phantom. This led to evaluate the total effective dose about 1.2 fold more than the cubic water phantom. However, it was still less than the permitted amount of annual public exposure according to ICRP 103(13).

Among all studied cases, a 3cm layer of bismuth covered the inner collimator walls and a 6cm thick layer of tungsten surrounded neutron sources created best uniformity of neutron activation rate and caused to a desirable increase in the sensitivity and decrease in the effective dose. It should be noted that, there are four ²⁴¹Am-Be sources in the IVNAA facility, and in the present study a pair was embedded on top and the other pair was on the bottom. In our experiment, we estimated that 10 minutes exposure is enough time to obtain good measurements. During this period, calculated effective dose in the absence and presence of best shielding was 0.172 mSv and 0.0816 mSv, respectively which has a good agreement with Borovnicar, Miri, Beddoe, Nydegger, and Haas works(7,8,11,23-25).

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14. Hakimabad, H. M., motavalli, L. R., Sepehri, F. Comparison between two approximations of effective dose in an IVNAA facility. (to be submitted).


Fig. 1 - schematic of IVNAA facility
264x407mm (300 x 300 DPI)
Fig. 2 - the calculated total organ dose equivalent in one minute in presence of different γ shield and absence of that

279x215mm (300 x 300 DPI)
Fig.3- the calculated Effective dose in one minute in presence of different γ shield and absence of that.

279x215mm (300 x 300 DPI)
Fig. 4 – Thermal neutron flux on the whole phantom 279x215mm (300 x 300 DPI)
Fig. 5 – Sensitivity of facility in different case of shield

279x215mm (300 x 300 DPI)
Fig. 6 – CV values of total body in different case of shield
279x215mm (300 x 300 DPI)
Table 1 - the percentage of reduction of organ dose equivalent

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<th>Tissue</th>
<th>Bi</th>
<th>W</th>
<th>Bi</th>
<th>W</th>
<th>Bi</th>
<th>W</th>
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<td>Lungs</td>
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<td>66.47</td>
<td>23.66</td>
<td>55.83</td>
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<td>53.44</td>
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<td>Gonads (testes)</td>
<td>29.68</td>
<td>65.79</td>
<td>20.72</td>
<td>51.31</td>
<td>15.59</td>
<td>48.09</td>
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<td>Gonads (ovaries)</td>
<td>33.94</td>
<td>69.39</td>
<td>27.51</td>
<td>57.21</td>
<td>25.12</td>
<td>57.93</td>
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<td>Bone surface</td>
<td>33.17</td>
<td>65.86</td>
<td>20.93</td>
<td>47.99</td>
<td>19.81</td>
<td>52.98</td>
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<td>Bone marrow</td>
<td>32.64</td>
<td>65.48</td>
<td>20.32</td>
<td>47.49</td>
<td>18.24</td>
<td>51.53</td>
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<tr>
<td>Colon</td>
<td>34.8</td>
<td>68.87</td>
<td>26.29</td>
<td>57.86</td>
<td>23.63</td>
<td>57.18</td>
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Table 2 - Comparison the calculated dose with Borovnicar, Beddoe, Nydegger, and Hass experiments in absence of the shield (7, 8, 23-25)

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<th>Type of source</th>
<th>Total dose</th>
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<tr>
<td>This work</td>
<td>$^{241}$Am-Be</td>
<td>effective dose</td>
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<tr>
<td>Borovnicar</td>
<td>$^{252}$Cf</td>
<td>effective dose equivalent</td>
</tr>
<tr>
<td>Beddoe</td>
<td>$^{238}$Pu-Be</td>
<td>organ dose equivalent</td>
</tr>
<tr>
<td>Nydegger</td>
<td>$^{252}$Cf</td>
<td>effective dose equivalent</td>
</tr>
<tr>
<td>Haas</td>
<td>$^{252}$Cf</td>
<td>effective dose</td>
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Table 3-Comparison the calculated gamma dose equivalent with Miri work: in absence and presence of shield surrounded the source \(^{(11)}\)

<table>
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<th>Type of shield</th>
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<tr>
<td>This work</td>
<td></td>
</tr>
<tr>
<td>Without shield</td>
<td>7.80E-04</td>
</tr>
<tr>
<td>Bi</td>
<td>6.09E-04</td>
</tr>
<tr>
<td>W</td>
<td>6.05E-04</td>
</tr>
<tr>
<td>Miri</td>
<td></td>
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<tr>
<td>(soft tissue(10×20×20 cm(^3)))</td>
<td>6.46E-04</td>
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Table 4- Difference percentage of CV between any case of shielding and without shield and case having minimum CV

<table>
<thead>
<tr>
<th>Case of shielding</th>
<th>Compared to without shield (%)</th>
<th>Compared to lowest CV (%)</th>
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<tr>
<td></td>
<td>CV</td>
<td>$\phi_\text{m}$(mean value)</td>
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<tr>
<td>Without shield</td>
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<td>around the bed</td>
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<tr>
<td>Bi</td>
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<td>-10.96</td>
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<td>W</td>
<td>0.1</td>
<td>-53.18</td>
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<td>Around the sources</td>
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<tr>
<td>Bi</td>
<td>1.94</td>
<td>7.83</td>
</tr>
<tr>
<td>W</td>
<td>7.06</td>
<td>16.03</td>
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<td>Around the sources + inner collimator walls (3cm of Bi)</td>
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<tr>
<td>Bi</td>
<td>5.83</td>
<td>-10.52</td>
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<tr>
<td>W</td>
<td>-3.57</td>
<td>-7.92</td>
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