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# An effective dose assessment technique with NORM added consumer products using skin-point source on computational human phantom

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## HIGHLIGHTS

- We evaluate the exposure dose from the usage of NORM added consumer products.
- We suggest the method determining the MC source term based on the skin-point source.
- To validate the skin-point source, the organ equivalent doses were compared with that the modeling source.
- The skin-point source could be employed to efficiently evaluate the annual effective dose.

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## ABSTRACT

The aim of this study is to develop the assessment technique of the effective dose by calculating the organ equivalent dose with a Monte Carlo (MC) simulation and a computational human phantom for the naturally occurring radioactive material (NORM) added consumer products. In this study, we suggests the method determining the MC source term based on the skin-point source enabling the convenient and conservative modeling of the various type of the products. To validate the skin-point source method, the organ equivalent doses were compared with that by the product modeling source of the realistic shape for the pillow, waist supporter, sleeping mattress etc. Our results show that according to the source location, the organ equivalent doses were observed as the similar tendency for both source determining methods, however, it was observed that the annual effective dose with the skin-point source was conservative than that with the modeling source with the maximum 3.3 times higher dose. With the assumption of the gamma energy of 1 MeV and product activity of 1 Bq $g^{-1}$, the annual effective doses of the pillow, waist supporter and sleeping mattress with skin-point source was 3.09E-16 Sv $Bq^{-1}$ $year^{-1}$, 1.45E-15 Sv $Bq^{-1}$ $year^{-1}$, and 2,82E-16 Sv $Bq^{-1}$ $year^{-1}$, respectively, while the product modeling source showed 9.22E-17 Sv $Bq^{-1}$ $year^{-1}$, 9.29E-16 Sv $Bq^{-1}$ $year^{-1}$, and 8.83E-17 Sv $Bq^{-1}$ $year^{-1}$, respectively. In conclusion, it was demonstrated in this study that the skin-point source method could be employed to efficiently evaluate the annual effective dose due to the usage of the NORM added consumer products.


## 1. Introduction

Recently, in order to regulate the unwanted radiation exposure to the general public from the naturally occurring radioactive material (NORM), a law as called 'Act on safety radioactive rays around living environment' was enacted in Korea (Korea Legislation Research Institute, n.d.; Lim et al., 2014). Especially, the law specifies a regulation of the NORM added consumer products such as the pillow, sleeping mattress, and eye patch which are easily accessible to the general public. Furthermore, the nuclear regulatory (NRC) and the United States environment agency (EPA) established a guideline for the regulation of the NORM in 2010 (EPA, n.d.). Despite the growing concern of the radiation risk to the public, an appropriated method to accurately evaluate the exposure dose from the use of the NORM added consumer products has not yet been developed. In our previous study, the effective dose was evaluated with the Monte Carlo method using MCNPX (Ham et al., 2012) and the reference phantom of the international

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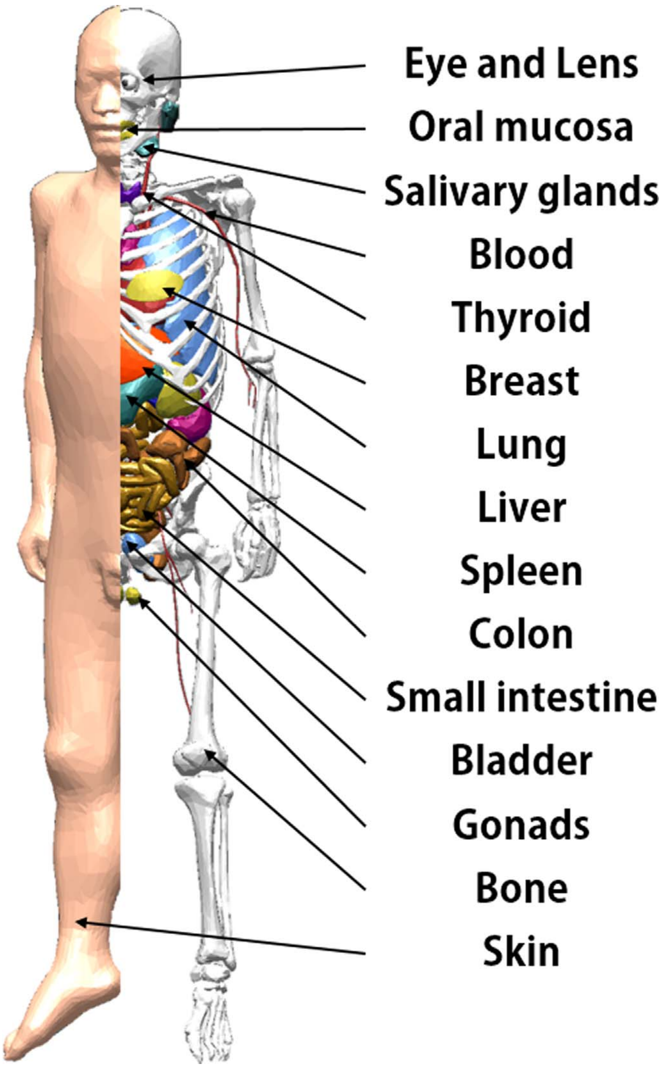


**Fig. 1.** Graphic rendering of the PSRK-Man phantom visualized with Geant4 tool kits with the representative organs for the evaluation of the effective dose.

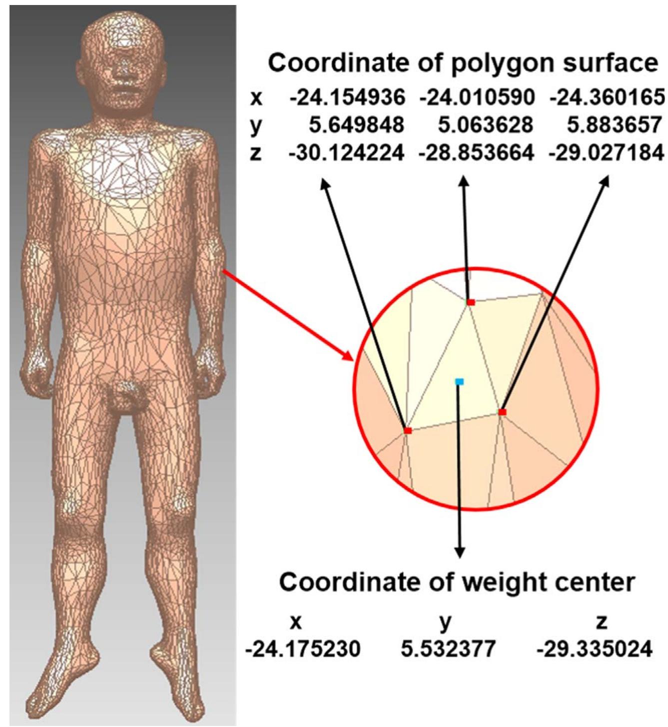


**Fig. 2.** Graphic rendered images of the skin that was composed of the polygon surface (left) and the three points forming one of the polygons on the skin with the weight center (right).

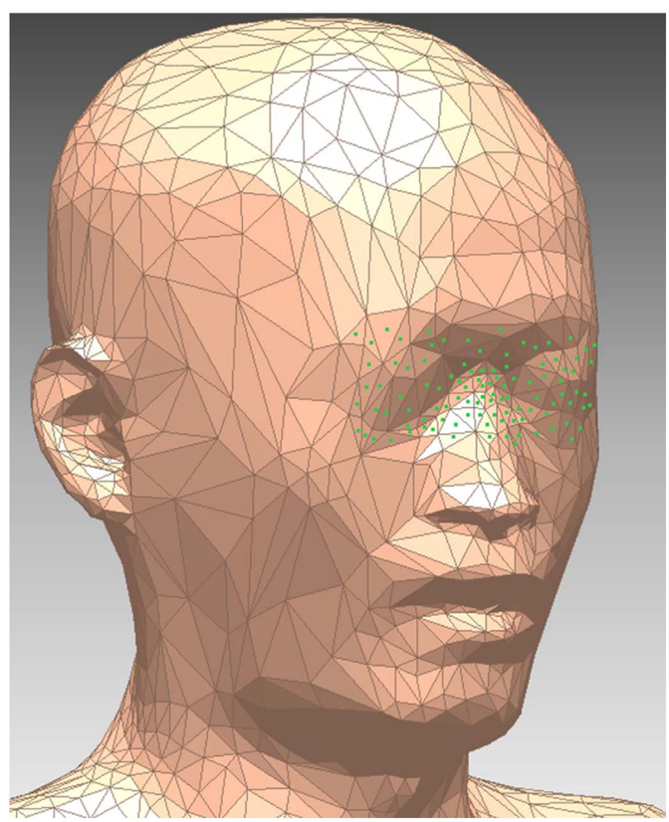

**Fig. 3.** The skin-point source near the usage location of the eye patch in the PSRK-Man phantom.

commission on radiological protection (ICRP) (Grosswendt, 2012) by modeling the sources with the realistic shape and usage locations (Yoo et al., 2014; Lee et al., n.d.). However, because of the variety types of the consumer products, the modeling for whole the consumer products is a significant burden for the radiation safety control. It is needed that the development of a new source term that can easily and correctly represent the source distribution. In this study, we developed the flexible source modeling method, called as skin-point source in which the precalculated organ dose and effective dose are selected according to the product location.

## 2. Materials and methods

### 2.1. Monte Carlo simulation and computational human phantom

The effective dose cannot be directly measured on the human body. So, the computational human phantom is widely used to evaluate the effective dose in the radiation protection field. The Polygon Surface Reference Korean Male phantom (PSRK-Man) developed by Hanyang University was employed in this study (Kim et al., 2011). The PSRK-Man was composed of 128,850 high resolution polygons to represent the 26 organs (Fig. 1) to calculate organ equivalent dose from the internal and external radiation exposure as defined in ICRP Publication 103 (Protection, 2007) except red bone marrow (RBM), lymphatic node, and extrathoracic

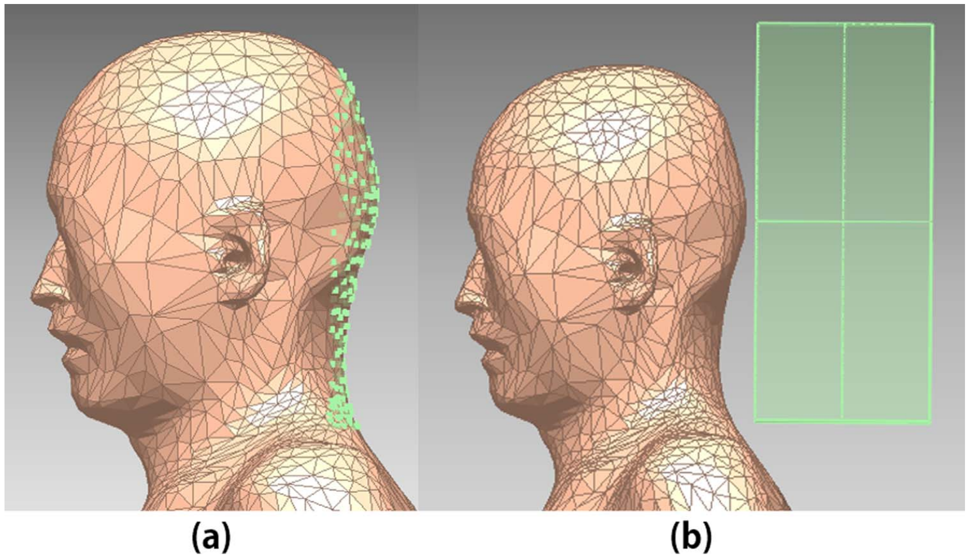


**Fig. 4.** The skin-point source (a) and the modeling source of the pillow product (b) for comparison of organ equivalent dose and effective dose.

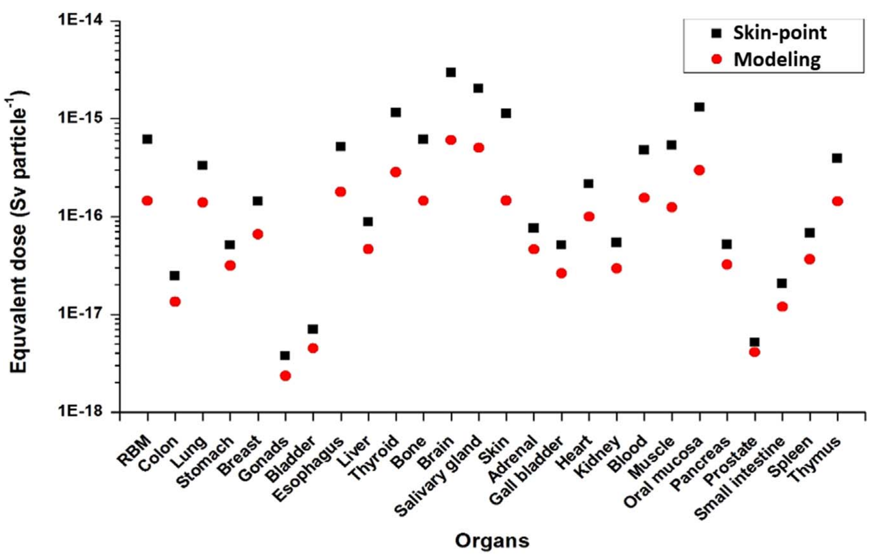


**Fig. 5.** The organ equivalent doses for the 26 organs of the PSRK-Man phantom for the pillow product with the skin-point source and modeling source methods.

region (ET region). In case of the RBM and lymphatic node, their organ equivalent dose were replaced by the doses of the entire skeleton system and blood, respectively (Cristy and Eckerman, n. d.). The extrathoracic region which is one of the remainder organs out of 13 was not considered, so the equivalent dose of the remainder was calculated with 12 organs. The PSRK-Man was developed based on the reference Korean male with the height and weight of 171-cm and 68-kg, respectively (Park et al., 2006). The exposure dose was evaluated by using Geant4 versions 10.02 which could be used for the general purpose for the radiation protection and dosimetry with the very high flexibility in defining the source term with various geometries (Choi et al., 2016). The PSRK-Man was also simulated with Geant4 tool kits. The dose calculations were performed using the computer equipped with a 2.93 GHz Intel Core 2 Quad Processor and 8 GB RAM. The annual effective dose was calculated with following equation:

$$D_{eff}\left(\frac{Sv}{year}\right) = \left(\sum_{1}^{29} w_i\, D_{equvalent\ dose}\left(\frac{Sv}{particle}\right)\right) \times t_{scenario}\left(\frac{second}{year}\right) \quad (1)$$

where $w_i$ is the tissue weighting factor and $D_{equivalent\ dose}$ is the organ equivalent dose, and $t_{scenario}$ is the annual usage time of each consumer product. Also, the usage time of the each consumer product was determined with the time-use study in the statistics Korea.

### 2.2. Determination of the skin-point source

As mentioned above, the PSRK-Man was composed of the polygons, and these polygons are composed of three points with three dimensional coordinates in each point as shown in Fig. 2. By using these coordinates on the skin, the skin-point source was determined as follows. First, whole the points on the skin were selected and the weight centers were calculated for each polygon. Second, the gammas were generated on the each weight center and the organ equivalent doses were recorded for each case of the gamma energy; that is, the doses were calculated according to the gamma energy ranged from 0.1 to 2.0 MeV with the interval of 0.1 MeV. Third, the region of the product was determined and the skin-point sources on that region were selected. Finally, the annual effective dose was evaluated with the organ equivalent dose assessed by the skin-point sources and the exposure scenario

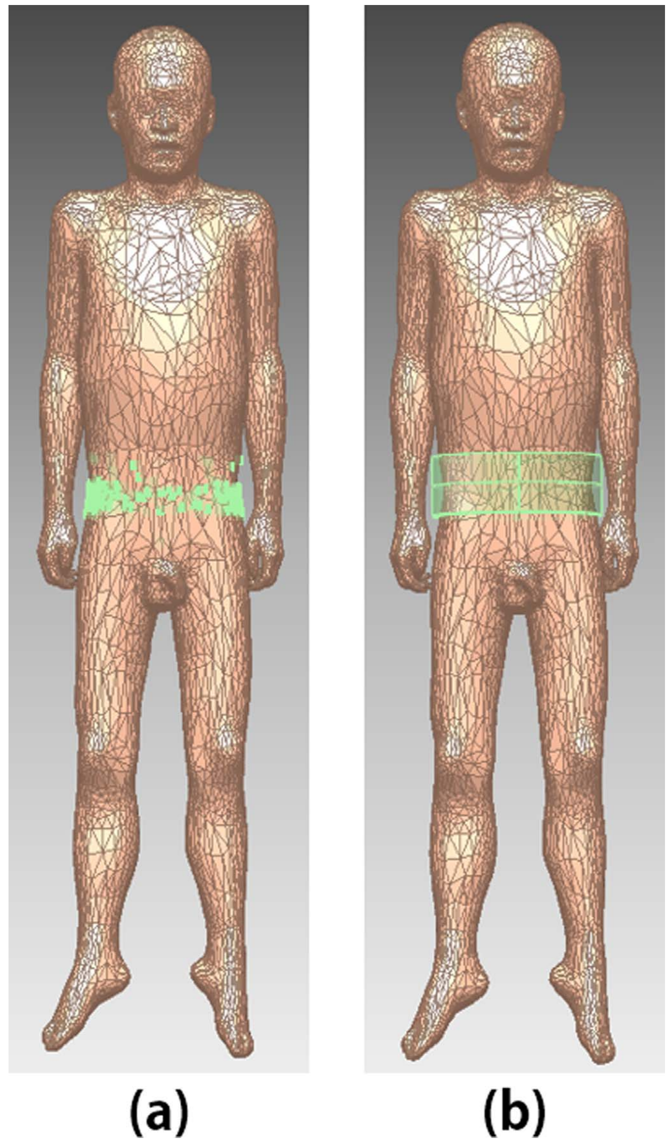


**Fig. 6.** The waist supporter products with the skin-point source (a) and the modeling source of the waist supporter product (b) for comparison of organ equivalent dose and effective dose.

considering the usage time of the product based on the report of the Statistic Korea. For example, the eye patch was usually used in front of the eyes during the sleeping time. So, the skin-point sources were selected near the eye as illustrated in Fig. 3. Then, the organ equivalent dose was assessed by the skin-point source with the exposure scenario of the eye patch assumed as used during the sleeping time which is surveyed as the average usage time of 7 h 50 min by the Statistic Korea (Report on the time use survey, 2009). In order to validate the skin-point source method, the organ equivalent dose was compared with the results by the modeling source method indicating the source generation in the real shape of the product.

## 3. Results and discussions

### 3.1. A pillow

Fig. 4 shows the skin-point source and the modeling source of the pillow product. The modeling source of the pillow products was generated in the rectangular parallelepiped space of 30-cm width, 50-cm length, and 13-cm height. The dimension of the pillow was determined with the normal size advertised in the korean market. The skin-point source for the pillow products were determined in the back of the human head and neck area; that is, the ranges of the x, y, and z coordinate in the phantom was $-9$ cm to 9 cm, 6 cm to 9 cm, and 72 cm to 85 cm, respectively. The organ equivalent dose of the skin-point source and the modeling source are compared as shown in Fig. 5. The results indicates the similar tendency of the two source term methods. However, the organ doses with the skin-point source generated on the skin surface and more closer to the critical organs were assessed as higher than the organ dose of the modeling source; for example, the organ equivalent dose in brain was calculated as 2.94E-15 and 6.03E-16 Sv particle$^{-1}$ for the skin-point source and modeling source, respectively. The organs close to the sources such as brain, salivary gland and oral mucosa shows relatively high equivalent dose with 2.94E-15, 6.03E-16, and 2.03E-15 Sv particle$^{-1}$, respectively than the equivalent dose of the organs far from the source as like the bladder, gonads and prostate of 6.97E-18, 4.49E-18, and 3.74E-18 Sv particle$^{-1}$, respectively. With the assumption of 1-MeV monoenergetic gamma ray and 1 Bq g$^{-1}$ radioactivity with the exposure scenario of 7 h 50 min usage time, the annual effective

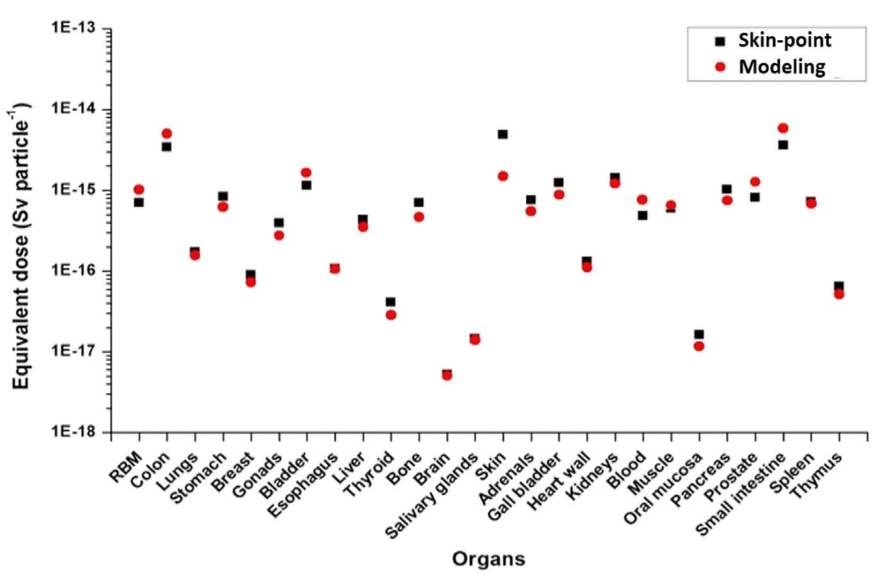


**Fig. 7.** The organ equivalent doses for the 26 organs of the PSRK-Man phantom for waist supporter products with skin-point source and modeling source.

dose of the pillow products with the skin-point source was about 3.3 times higher than that with the modeling source with 3.09E-16 and 9.22E-17 Sv Bq$^{-1}$ year$^{-1}$, respectively.

### 3.2. A waist supporter

Usually the waist supporter is used around the abdomen area. To validate the skin-point source of the waist supporter, the modeling source was generated in the cylindrical shape of 30-cm radius and 10-cm height. Also the skin-point source of the waist supporter was determined in the area of the waist in the phantom; that is, the ranges of the x, y, and z coordinate in the phantom was −17 cm to 15 cm, −10 cm to 12 cm, 0 cm to 20 cm, respectively (Fig. 6). The organ equivalent dose of the skin-point source and the modeling source are compared as shown in Fig. 7.

The organ equivalent dose close to the abdominal region of colon, small intestine, kidney, and gall bladder were assessed as higher than the other organs. Similar to the pillow products, it is observed with waist support case that the dose with the skin-point source mostly shows higher than that of the modeling source. However, the dose difference with the two methods was assessed as reduced with the similarity of the source position surrounding the abdomen. The annual effective dose was calculated in the same gamma energy and radioactivity conditions as pillow products with the exposure scenario of 5 h 1 min usage time, the annual effective dose of the waist supporter with the skin-point source was about 1.47 times higher than that with the modeling source with of 8.52E-16 and 5.79E-16 Sv Bq$^{-1}$ year$^{-1}$, respectively (Fig. 8).

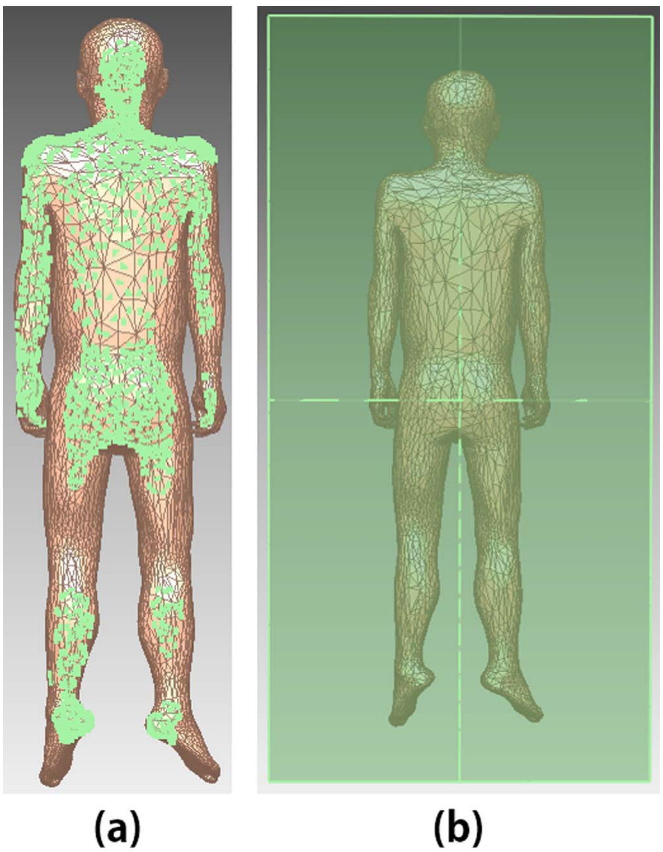


**Fig. 8.** The sleeping mattress products skin-point source (a) that are considered of maing usage location and the modeling source of the waist supporter product (b) for comparison of organ equivalent dose and effective dose.

### 3.3. A sleeping mattress

The modeling source of the sleeping mattress was generated in the rectangular parallelepiped space of 100-cm width, 200-cm length and 1-cm height. The dimension of the sleeping mattress was determined with the single sized mattress. It is assumed that the sleeping mattress is usually used on the backside of the human body during the sleeping time. So, the location of the skin-point source was determined on the backside of the human phantom area; that is, the ranges of the −15 cm to 18 cm, 6 cm to 9 cm, and −70 cm to 85 cm, respectively. Unlike the pillow and the waist supporter products, the sleeping mattress has a wide source area, and all of the organs are located near the source. The organ equivalent dose result shows adequately similar values over the organs in both source terms as shown in Fig. 9. With the exposure scenario of 7 h 50 min usage time, the annual effective dose with the skin point source was about 3.2 times higher than that with the modeling source with 2.82E-16 and 8.83E-17 Sv Bq$^{-1}$ year$^{-1}$, respectively.

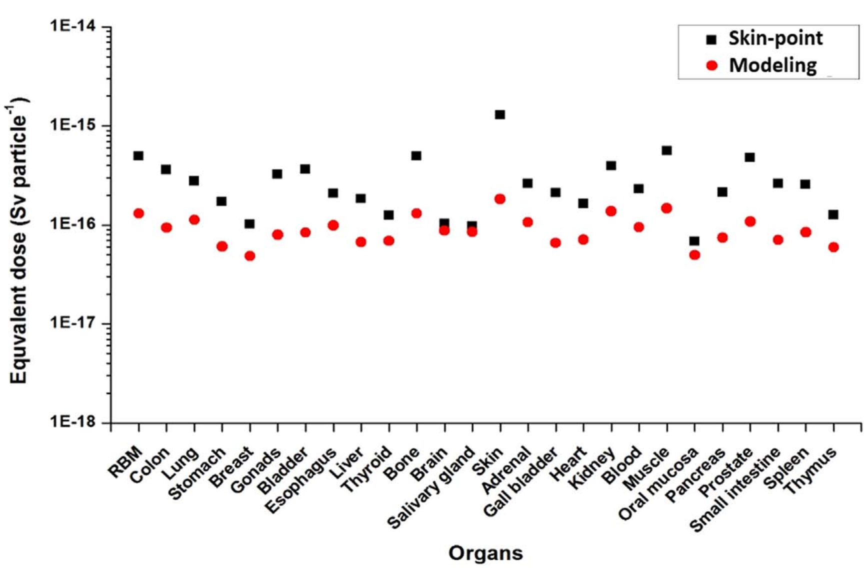


**Fig. 9.** The organ equivalent dose for the 26 organs of the PSRK-Man phantom for sleeping mattress products with skin-point source and modeling source.

## 4. Conclusions

This study demonstrates the feasibility of evaluating the effective dose by the usage of NORM added consumer products using Monte Carlo simulations and PSRK-man phantom. To assess the exposure dose, this study suggest “skin-point source” methods. The organ equivalent dose and the annual effective dose calculated by the skin-point source are mostly higher than those calculated by the modeling source, even though both models show similar tendency in the organ equivalent doses. The skin-point source could be effectively used in determining the annual effective dose for the various products by selecting the exposure scenario and the usage location of the product. Moreover, the pre-calculated database for the organ equivalent dose in whole the polygons with 0–2 MeV photons would enable the rapid assessment of the effective dose without additional Monte Carlo simulation demanding the advanced programming knowledge with radiation physics background. For the precise evaluation of the annual effective dose according to its original definition averaging the organ dose of male and female, additional study will be carried out with the female human phantom. This technique could be used not only for the safety regulation for the products containing NORM but also for the accurate and rapid evaluation of the effective dose for the radiation workers in the diverse radiation field.

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