Library of Mesh and NURBS female phantoms for pulmonary in vivo counting studies

J. Farah[1], D. Broggio[1], J. Henriet[2], L. Makovicka[2] and D. Franck[1].

[1] Internal Dosimetry Department, Institut de Radioprotection et de Sureté Nucléaire, 31 avenue de la division Leclerc Fontenay-aux-Roses, 92260 France.

[2] FEMTO-ST/ENISYS/IRMA, Université de Franche Comté, 4 place Tharradin BP 71427, F-25211Montbéliard, France.

Abstract

To optimize the monitoring of female workers, numerical calibration of in vivo counting systems was carried out using a library of 24 female thoracic phantoms with various chest girths (85-120) and cup sizes (A-F) combined with Monte Carlo simulations. The morphology-induced variations of counting efficiency were thus quantified and put into equation. This paper focused on establishing a simple method to correct the efficiency calibration curve obtained with the Livermore male phantom, taking into account the breast size. As a result, lung efficiency corrections were tabulated for the 24 designed female torso models and the AREVA NC in vivo counting system. Using the developed morphological equation the corrections were also given for breast sizes not included in the library. In this work, alternative detector positioning was also investigated to further increase the counting efficiency that is significantly reduced by female breasts. It was found that positioning the detectors in the back of the subjects significantly improve detection limits in the case of large breasts and such positioning is worth being further investigated. Finally, a case-base reasoning platform was developed to go much further towards personalized numerical calibrations.

Keywords: in vivo monitoring, deformable phantoms, Monte Carlo simulations, female correction factors.

I. Introduction

In vivo spectrometry measurements are commonly used to monitor workers with internal contamination risks. However, one of the main drawbacks in the calibration of counting systems is the use of physical phantoms, such as the Livermore phantom (Griffith et al. 1978), that remain of limited realism in regards to the human anatomy. For *in vivo* lung monitoring of female workers, no physical female phantom dedicated for the calibration of *in vivo* installations exists. The use of the typical male-based calibration coefficients results in high uncertainties on the activity estimate, and consequently on the dose calculation for female workers. Therefore, numerical calibrations based on MC calculations are needed to optimize the monitoring of female workers using *in vivo* spectrometry measurements (Franck et al. 2003). This work was thus undertaken as part of PICDOSINTER, a collaboration project between AREVA NC and the French Institute for Radiological Protection and Nuclear Safety (IRSN).

The work was based on the use of deformable Mesh and NURBS geometries (Xu and Eckerman 2009) to carry out numerical calibrations of the AREVA NC *in vivo* counting system and correct the typical calibration coefficients obtained with the male torso phantom. The work has led to the development of a library of torso phantoms representing the most common female sizes and morphologies (Farah et al. 2010a). The work also involved the use of the OEDIPE software (Franck et al. 2007) to reproduce a realistic *in vivo* measurement and the Monte Carlo MCNPX code (Pelowitz 2005) to simulate a pulmonary contamination. Moreover, an equation describing the morphological dependence of lung counting calibration coefficients was developed and validated by direct comparison against simulated data, experimental results and published data (Farah et al. 2010b). Finally, the Equivox platform was developed to perform realistic and personalized dosimetry in emergency cases involving accidental internal contamination situations (Farah et al. 2011). Case-based reasoning principles and artificial neural network tools were thus introduced to select and adapt from the library, the most similar phantom to the contaminated subject for whom no numerical model exists.

Additional work was nonetheless necessary to bring a simple, practical and easy-to-use method in routine that would help optimize the monitoring of female workers and carry out personalized dosimetry. On the one hand, a practical method was given to determine calibration curves specific for each counting system and accounting for the monitored female's breast size and morphology. On the other hand, additional investigations were carried out to consider alternative detector positioning to further improve the detection limits in the case of female workers.

This paper highlights some of the key results and introduces the main conclusions and recommendations given to optimize the in vivo lung monitoring of female nuclear workers.

II. Materials and methods

A brief summary of the library results and those of the morphological equation are first presented in this section. These findings represent the primary materials for the establishment of conversion coefficients and for the improvement of *in vivo* counting through alternative detector positioning.

II.1. Deformable models and morphological equation

- **Library of deformable female phantoms**

A library of 24 thoracic female phantoms, derived from the torso of the ICRP adult female reference computational phantom (ICRP 2009), was developed. These models were created to represent the most common female morphologies by varying chest girth (85 to 120), cup size (A to F) and internal organ volume according to relevant publications (CEN 2004, Clairand et al 2000, Turner and Dujon 2005). To carry out the morphological adjustments, the ICRP reference voxel female was first transformed into Mesh and NURBS geometries. Next, target values for each parameter (chest girth, cup size and internal organ volume) were set and the deformable core model was transformed into the 23 target models by using the Rhinoceros 3D (Rhino 3D) modeling software (McNeel & Associates www.rhino3d.com). Figure 1 represents the deformable core model equivalent to the ICRP reference female and illustrates the 3D modeling operations to adjust cup size using the NURBS control points. The breast size influence over the counting efficiency was studied using a gamma source emitting 17 photons of energies ranging from 15 keV to 1.4 MeV. Monte Carlo simulations showed a decrease in counting efficiency, as much as 50%, between the A and the E cup for one particular chest girth. Moreover, for a given cup size, the counting efficiency variation with chest girth was quantified and proven to be extremely severe for low energy photons.

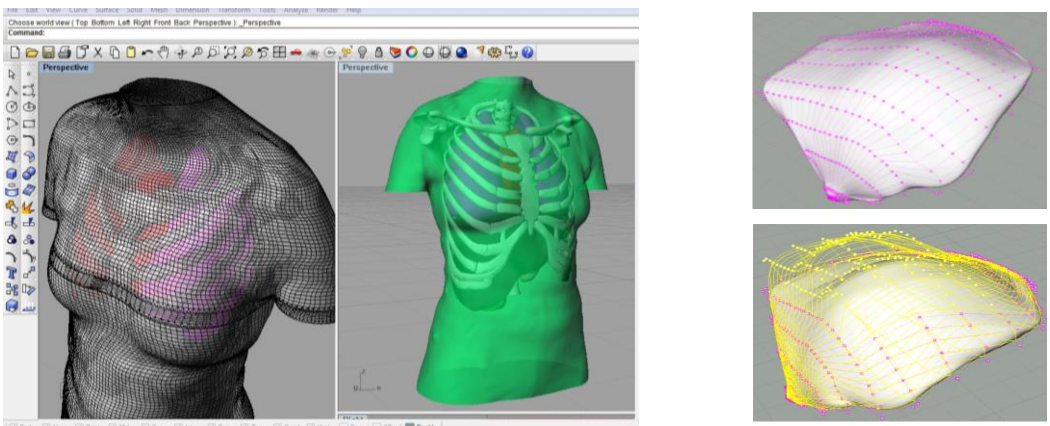

Figure 1. Rhino 3D visualization of the deformable core torso created from the ICRP reference female (left) and the manual deformation of breasts' NURBS control points (right).

- **Morphological dependence of in vivo counting efficiency**

The morphology-induced variations of counting efficiency as a function of photon energy were next put into equation to enable a realistic estimate of detectors' counting efficiency for each monitored female subject. The changes in morphology for the developed female models include variation in chest girth, cup size and lung volume (loaded organ). Such differences induce exponential radiation attenuation with tissue thickness and an inversely linear trend with lung volume. Thus, the relationship between two counting efficiencies was simply written as:

$$\varepsilon_2(E) = \varepsilon_1(E) c_1 e^{-c_2\,\mu(E)} \qquad \text{(Equation 1)}$$

where ε_1 represents the reference counting efficiency, ε_2 the unknown efficiency, E the photon energy, c_1 is the parameter representing the effect of lung volume variation while c_2 represents that of cup size. Finally, the function $\mu(E)$ is the mass attenuation coefficient for ICRU-44 (ICRU 1989) adipose tissue obtained using the online NIST-XCOM tool (Berger et al. 2005).

This equation was next validated by comparison against MC simulation data, experimental results and published data (Hegenbart et al 2008). Figure 2 compares the counting efficiency value given by the developed equation against the simulation results obtained using MCNPX and different models from the female library. These results were obtained taking the 85A simulated curve as the reference efficiency (ε_1). Similar results were obtained when starting from the Livermore P4 measured curve or from the Hegenbart et al (2008) 105AA curve (Farah et al. 2010b).

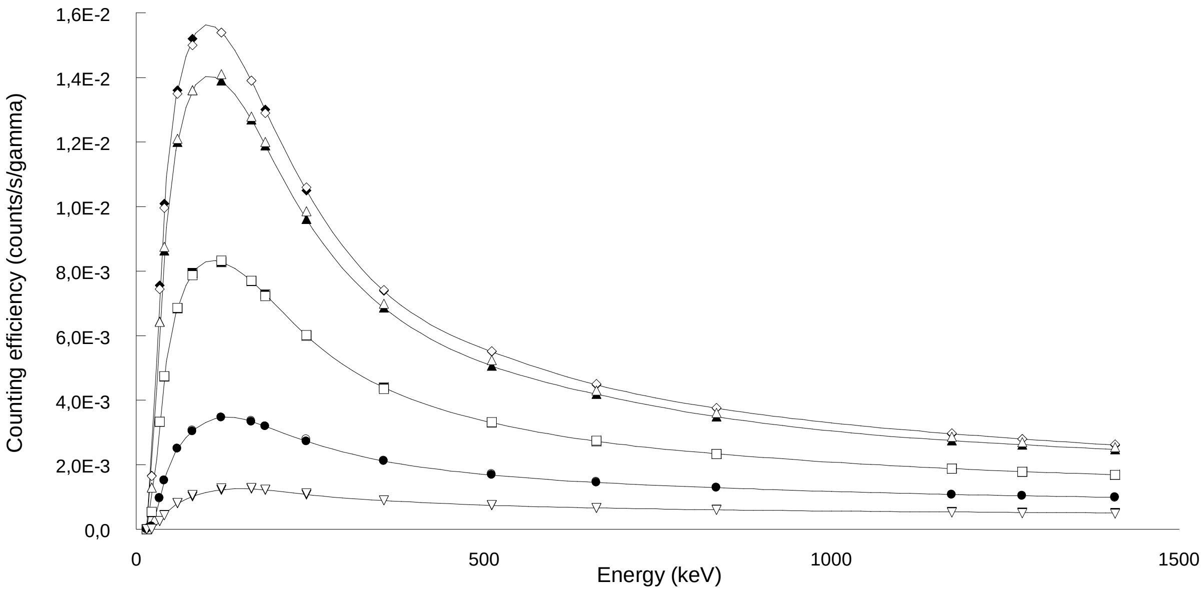

Figure 2. MC simulated counting efficiencies (black symbols and solid lines) against the equation values (white symbols) for the: 85B (diamonds), 90C (triangles), 100D (squares), 110E (dots) and 120F (inverted triangles).

II.2. Conversion factors: practical recommendations for routine use

The developed library includes 24 female models representing the most common but not all possible female morphologies. Moreover, even if the developed equation produces rapid and reliable estimates of efficiency curves, it remains of limited interest since it is based on simulated data that is rarely available in routine. Conversion factors are thus needed to optimize the *in vivo* calibration process for any female morphology but starting from experimental calibration curves obtained with the Livermore phantom.

- **Method to estimate the efficiency for different female morphologies**

For females with unusual body size and shape that are not represented in the created female torso library, the typical calibration coefficients require sensitive corrections in order to estimate realistic and personalized calibration coefficients. This explains the need for a method that would help estimate the efficiency for any female by considering the morphological differences with the available models of the library. Then, it would be possible to use the developed equation and the simulation results to assess realistic calibration curves.

The method consists in using the bra size to determine internal parameters that are difficult to reach such as chest wall thickness and lung volume and which directly affect the count. A relationship between the morphological parameters was thus determined starting from the simulation results and the female library.

- **Method to transform a measured curve into a female one**

Since the reference curve used by this equation, a simulation result, is often unavailable for routine measurements optimization, it is of outmost importance to investigate if a calibration measurement of the Livermore phantom can be used as the reference efficiency curve. The idea is to find, for each female individual, the correct equivalent combination of the Livermore male torso with the adequate physical chest plate (or combination of plates) and the appropriate detector positioning that would represent the same efficiency attenuation that would be obtained due to breasts.

The method consists in comparing the available Livermore measurements (with plates P0 to P4), with the 24 simulation results. If two calibration curves are found equivalent, then the measured curve could be directly used as the reference of the developed equation (ε_1). Otherwise, the morphological differences between the Livermore physical male phantom and the monitored female worker, i.e. chest wall thickness and lung volume, should be assessed to adjust the Livermore curve to the female morphology.

II.3. Alternative detector positioning: a mean to improve the counting efficiency

When conducting MC simulations with the developed library of female phantoms, detectors were positioned facing the lungs and brought as close as possible to the skin, reproducing as faithfully as possible the measurement protocol.

However, such a detector positioning remains far from being optimal to maximize the *in vivo* counting since breasts highly attenuate the radiations coming from the lungs. Alternative positioning of the detectors in the back of the subject was thus investigated. Indeed, for large breasts, it is expected that the back positioning will results in an increase of the counting efficiency. This investigation can only be carried out with the developed models since the Livermore phantom does not contain scapulae attenuating the radiation coming from the lungs.

III. Results and discussion

III. Conversion factors: practical recommendations for routine use

- **Method to estimate the efficiency for different female morphologies**

From the simulation results, the morphological parameters were studied to determine whether or not any relationship could be identified. Figure 3 plots parameter c_1 (related to organ volume) as a function of parameter c_2 (related to chest wall thickness) revealing a linear correlation. Using the linear equation of this plot, it is possible to estimate the morphological parameter c_1 when knowing the value of parameter c_2. The latter parameter accounts for breast size and can be easily estimated from the bust circumference or using the method below. Once both morphological parameters are available, it becomes possible to estimate any counting efficiency using the developed equation.

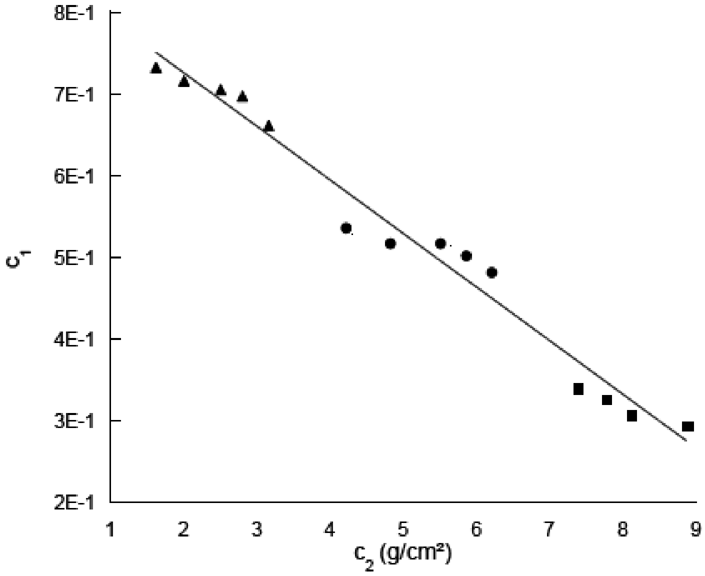

Figure 3. Variation of c_1 as a function of c_2 (g/cm²) for chest girths of 100 (triangles), 110 (dots) and 120 (squares), with all cup sizes represented. Linear fit calculated using Microsoft Excel 2008^{TM}: y = -0.0656 x + 0.8574, R^2=0.9728.

For example, this equation could be used to determine the efficiency value for a 105D female individual which was not covered by a numerical model in this study. According to Turner and Dujon (2005), the weight increment for an increase of one cup size is the same for the 105 and 110 chest girths. Moreover, following recommendations by Wood et al (2008), it is legitimate to associate values in pairs (105D/110C) and consider that both models have the same c_2 value of 4.87 g/cm². When using the equation given in the caption of Figure 3, a c_1 value of about 0.52 is obtained. Entering these parameters in the developed equation gives, for the 105B phantom, a counting efficiency of about 3.3E-03 counts/s/gamma for Am-241 photons at 59.54 keV. This counting efficiency value can be considered as reasonably correct since it is less than the one obtained for the 100D phantom (6.85E-03 counts/s/gamma), but greater than the one for the 110D model (2.68E-03 counts/s/gamma). Other examples are given in Farah et al. (2010a). It is suggested to use this method to estimate the counting efficiencies when no phantom exists.

- **Method to transform a measured curve into a female one**

When comparing the Livermore measurements (with chest plates P0 to P4), it was found that the 85A female simulated curve was significantly equivalent to the Livermore-P1 efficiency curve. Indeed, the maximum relative error between the measured and the simulated counting efficiencies was less than 5% for all energies higher than 59.54 keV. For lower energies, noticeable difference were observed (up to 35% for 22 keV) but can be explained by the materials used in the Livermore that does not exactly reproduce the absorption of gamma radiation in human tissues. Equation 1 was thus used with the Livermore-P1 efficiency curve as a reference (ε_1). As a result correction factors for the P1-Livermore efficiency curves where finally tabulated for all breast sizes and energies of interest. Table 1 gives the correction factors for the germanium detectors of the AREVA NC *in vivo* monitoring installation and various breast sizes. This table takes into account the efficiencies obtained with the 24 female phantoms and also those deduced for female subjects not represented in the library.

As a partial conclusion, similar conversion factors could be determined now specifically for a counting system when using the available Livermore measurements. The recommendations given here to estimate the morphology-induced variations of counting efficiency for each female worker should be used and the obtained coefficients can again be compared to the ones presented here to further validate the suggested method and to increase the confidence in the obtained results.

Table 1. Conversion factors to correct the Livermore P1 measurement as a function of female size (E_{ff} = E_{ff} Livermre / factor).

Size		Energy (keV)																
		15	22	33	40	59	81	122	165	185	244	356	511	661	834	1173	1274	1408
85	A	1.09	1.35	1.23	1.18	1.08	1.00	1.01	1.01	1.01	1.00	1.02	1.03	1.03	1.01	1.05	1.04	1.01
	B	2.68	1.97	1.53	1.43	1.27	1.16	1.09	1.08	1.09	1.12	1.13	1.07	1.06	1.08	1.11	1.10	1.07
	C	3.57	2.33	1.72	1.60	1.39	1.26	1.17	1.15	1.16	1.17	1.18	1.12	1.10	1.11	1.14	1.13	1.09
	D	4.93	2.63	1.83	1.68	1.45	1.30	1.21	1.19	1.19	1.22	1.21	1.15	1.12	1.14	1.16	1.15	1.11
	E	7.01	3.21	2.09	1.90	1.62	1.45	1.33	1.29	1.29	1.31	1.29	1.23	1.19	1.20	1.22	1.20	1.16
90	A	2.05	1.75	1.42	1.36	1.21	1.10	1.05	1.04	1.06	1.09	1.09	1.06	1.06	1.08	1.11	1.10	1.06
	B	4.05	2.35	1.69	1.58	1.37	1.24	1.17	1.15	1.16	1.18	1.18	1.13	1.12	1.14	1.16	1.15	1.11
	C	4.49	2.54	1.80	1.67	1.44	1.30	1.21	1.19	1.19	1.22	1.22	1.16	1.13	1.16	1.19	1.17	1.13
	D	5.68	2.85	1.94	1.79	1.52	1.37	1.27	1.25	1.26	1.28	1.26	1.19	1.16	1.18	1.20	1.19	1.15
	E	8.51	3.49	2.19	1.99	1.67	1.48	1.36	1.32	1.33	1.35	1.33	1.25	1.22	1.21	1.23	1.22	1.17
95	A	5.31	3.03	2.09	1.89	1.68	1.62	1.58	1.56	1.56	1.54	1.52	1.49	1.48	1.46	1.41	1.40	1.38
	B	6.20	3.26	2.19	1.97	1.75	1.68	1.63	1.80	1.61	1.59	1.56	1.53	1.51	1.49	1.44	1.43	1.41
	C	8.06	3.71	2.39	2.13	1.87	1.78	1.73	1.70	1.69	1.67	1.63	1.60	1.57	1.55	1.50	1.48	1.46
	D	12.54	4.60	2.75	2.42	2.09	1.98	1.91	1.87	1.85	1.82	1.77	1.72	1.69	1.65	1.59	1.57	1.54
	E	21.50	5.99	3.28	2.84	2.41	2.26	2.15	2.09	2.07	2.02	1.95	1.88	1.84	1.79	1.72	1.69	1.66
100	B	8.16	3.80	2.56	2.35	2.01	1.81	1.68	1.65	1.66	1.68	1.69	1.60	1.56	1.58	1.60	1.59	1.54
	C	12.11	4.79	2.96	2.67	2.24	2.00	1.84	1.78	1.79	1.81	1.78	1.69	1.65	1.65	1.65	1.64	1.59
	D	20.38	6.17	3.47	3.05	2.51	2.22	2.03	1.96	1.95	1.96	1.90	1.78	1.74	1.73	1.75	1.72	1.65
	E	27.90	7.25	3.81	3.33	2.70	2.37	2.15	2.07	2.07	2.07	2.01	1.85	1.81	1.78	1.78	1.76	1.68
	F	41.56	9.20	4.51	3.87	3.09	2.71	2.44	2.33	2.31	2.28	2.19	2.00	1.95	1.90	1.87	1.87	1.79
105	B	12.27	4.55	2.73	2.41	2.08	1.97	1.90	1.86	1.84	1.81	1.76	1.71	1.68	1.65	1.59	1.57	1.54
	C	59.39	9.88	4.58	3.85	3.14	2.90	2.72	2.61	2.57	2.48	2.35	2.24	2.17	2.10	1.99	1.96	1.92
	D	96.79	12.58	5.40	4.46	3.58	3.28	3.05	2.91	2.86	2.74	2.58	2.45	2.36	2.28	2.14	2.10	2.06
	E	185.5	17.40	6.72	5.44	4.27	3.87	3.55	3.36	3.30	3.14	2.93	2.76	2.64	2.53	2.37	2.33	2.27
	F	1052	41.78	12.24	9.41	6.96	6.12	5.46	5.06	4.92	4.60	4.19	3.85	3.63	3.44	3.16	3.09	3.00
110	B	179.4	18.95	7.33	6.09	4.69	4.05	3.56	3.36	3.33	3.29	3.12	2.86	2.73	2.69	2.64	2.59	2.49
	C	325.6	24.68	8.72	7.10	5.34	4.58	3.99	3.74	3.71	3.63	3.39	3.07	2.91	2.85	2.78	2.72	2.60
	D	741	35.43	10.78	8.57	6.27	5.31	4.50	4.22	4.17	4.02	3.71	3.34	3.13	3.02	2.92	2.84	2.72
	E	988	40.34	11.98	9.47	6.87	5.79	4.84	4.51	4.45	4.30	3.94	3.51	3.27	3.15	3.06	2.98	2.82
	F	1359	47.22	13.49	10.56	7.57	6.34	5.35	4.92	4.83	4.63	4.21	3.72	3.46	3.35	3.19	3.10	2.94
115	C	776	35.80	11.00	8.53	6.38	5.64	5.05	4.70	4.58	4.30	3.93	3.62	3.43	3.25	3.00	2.93	2.85
	D	2529	65.54	16.74	12.54	9.00	7.81	6.86	7.00	6.09	5.65	5.08	4.62	4.32	4.07	3.70	3.61	3.50
	E	3768	80.59	19.35	14.33	10.14	8.75	7.63	6.96	6.74	6.22	5.56	5.03	4.69	4.40	3.99	3.89	3.77
	F	14639	164.8	32.21	22.92	15.52	13.10	11.17	10.04	9.66	8.80	7.72	6.87	6.33	5.89	5.27	5.12	4.94
120	C	6744	122.2	26.38	19.69	13.59	11.19	9.23	8.34	8.15	7.74	6.94	6.05	5.57	5.33	5.04	4.91	4.65
	D	10277	147.9	30.22	22.30	15.18	12.42	10.17	9.13	8.89	8.40	7.42	6.43	5.90	5.60	5.28	5.13	4.87
	E	15369	176.3	34.90	25.60	17.27	14.06	11.37	10.15	9.85	9.21	8.13	6.99	6.35	6.01	5.59	5.43	5.11
	F	35571	256	45.60	32.66	21.52	17.23	13.76	12.07	11.67	10.82	9.36	7.94	7.17	6.69	6.12	5.88	5.54

III.2. Alternative detector positioning: a mean to improve the counting efficiency

To reduce the radiation attenuation caused by breasts, simulations were conducted with the detectors in the back of the ICRP AF-RCP phantom. Another alternative detector positioning with the detectors on the sides of the phantom was also investigated. Figure 4 presents the MC simulation results obtained for the artificial photon source uniformly distributed in the lungs and compares the efficiency values obtained at different detectors positioning.

From this plot, it is clear that better counting efficiency values can be obtained, particularly at medium and high energies, when the positioning of the detectors is optimized. Indeed, a 35% increase in counting efficiency was observed when comparing the front and back detector positioning for the 511 keV photons. However, this is not the case for the lowest energy photons that are highly attenuated by the scapulae and spine and for which the efficiency dropped from 1.66E-03 counts/Bq/s (front position) to about 1.61E-03 counts/Bq/s (back position) for the 22 keV photons. Meanwhile, for detectors on the side of the phantom, no significant increase in counting efficiency was observed since detectors in the lower positions have a reduced solid angle with regards to the lungs, which limits the counts.

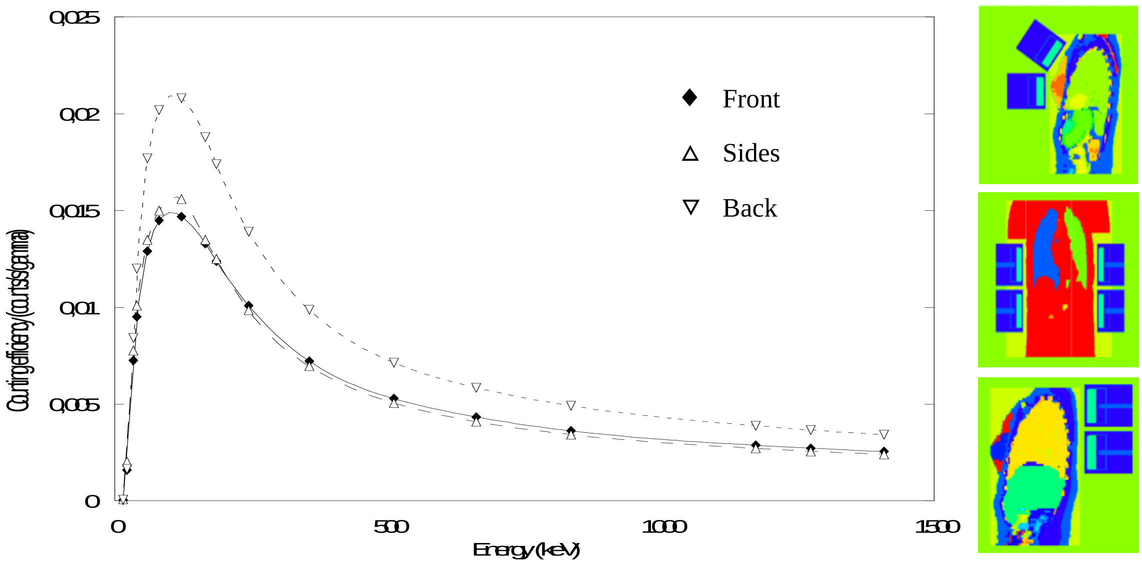

Figure 4. Counting efficiency variation with energy with the detectors positioned: (i) facing the breasts (diamonds), (ii) on the sides (triangles), (iii) in the back of the phantom (inverted triangles).

From this result, we suggest to investigate the possibility of developing not only a female torso phantom, but also to adjust the back of the Livermore phantom with scapulae. Besides, a new measurement protocol should be established in which the detectors would be set at the back of the subject to improve the counts and avoid sensible efficiency loss due to breasts.

IV. Conclusion

The library of female models developed in this study compensates for the lack of female physical phantoms for the routine calibration of *in vivo* counting installations. Mesh and NURBS geometries have proven to be very flexible and the simulation results provided specific counting efficiency curves for a typical set of four-germanium-detectors. A simple equation was also derived to determine the counting efficiency variation with morphology and reliable estimates of detector counting efficiency are now available for any female morphology to avoid time-consuming MC simulations.

Based on these findings, practical recommendations were given to adapt the Livermore measured calibration curves and to account for breast size. Moreover, additional information was given to assess conversion factors, specific for each counting system, and to take into account breast size not included in the developed library. This paper gives orders of magnitude of the correction coefficients to avoid sensitive dose-calculation errors while using Livermore calibration curves for female individual. Besides, based on the investigations related to alternative detector positioning, a new measurement protocol, where the detectors would be set at the back of the subject, was suggested to maximize the counts and optimize the detection limits. Finally, access to the developed library can be granted upon request, to conduct additional simulations, to consider alternative activity distributions or additional radionuclides in order to further improve monitoring programs.

Finally, the EquiVox platform (Farah et al. 2011) is being upgraded to enrich the case-base database with new and representative models and the adaptation algorithm is being improved to adjust a set of organs and structures and reconstruct a realistic and personalized torso phantom.

Acknowledgment

The authors gratefully acknowledge the support of the French Society of Radiation Protection and the nomination for IRPA-2012 Young Professional Prize.

References

Clairand I., Bouchet L.G., Ricard M., Durigon M., Di Paola M., Aubert B. Improvement of internal dose calculations using mathematical models of different adult heights. *Phys. Med. Biol.* **45**(10): 2771-2785; 2000.

European Committee for Standardization (CEN).Size designation of clothes: -part 3. Measurements and intervals EN 13402-3; 2004.

Farah J., Broggio D. and Franck D. Creation and use of adjustable 3D phantoms: application for the lung monitoring of female workers. *Health Phys.* **99**(5): 649–661; 2010a.

Farah J., Broggio D. and Franck D. Female workers and in vivo lung monitoring: a simple model for morphological dependency of counting efficiency curves. *Phys. Med. Biol.* **55**(23): 7377-7395; 2010b.

Farah J., Henriet J., Broggio D., Laurent R., Fontaine E., Chebel-Morello B., Sauget M., Salomon M., Makovicka L. and D. Franck. Development of a new CBR-Based platform for human contamination emergency situations. *Radiat. Prot. Dosim.* **144**(1-4): 564-570; 2011.

Franck D., Borissov N., de Carlan L., Pierrat N., Genicot J.L. and Etherington G. Application of Monte Carlo calculations to calibration of anthropomorphic phantoms used for activity assessment of actinides in lungs. *Rad. Prot. Dos.* **105**(1-4): 403-408; 2003.

Franck D., de Carlan L., Pierrat N., Broggio D. and Lamart S. OEDIPE: a new graphical user interface for fast construction of numerical phantoms and MCNP calculations. *Radiat. Prot. Dos*. **127**(1-4): 262–265; 2007.

Griffith R.V., Dean P.N., Anderson A.L. and Fisher J.C. Fabrication of a tissue-equivalent torso phantom for intercalibration of in-vivo transuranic-nuclide counting facilities. *Symp. Adv. Radiat. Prot. Monit.* (Stockholm, Sweden); 1978.

Hegenbart L., Na Y. H., Zhang J. Y., Urban M. and Xu X. G. A Monte Carlo study of lung counting efficiency for female workers of different breast sizes using deformable phantoms. *Phys Med. Biol.* **53**(19): 5527-5538; 2008.

International Commission on Radiological Protection Publication 110. Adult reference computational phantoms. *Ann. ICRP* **39**(2); 2009. (Oxford: Elsevier)

Pelowitz D.B. (ed). MCNPX User's manual version 2.5.0. Los Alamos National Laboratory Report *LA-CP-05-0369*; 2005.

Turner A.J. and Dujon D.G. Predicting cup size after reduction mammaplasty. *Br. Jr. Plast. Surg.* **58**(3): 290-298; 2005.

Wood K., Cameron M. and Fitzgerald K.. Breast size, bra fit and thoracic pain in young women: a correlational study. Chiropr. Osteopat. **16**: 1; 2008.

Xu X.G. and Eckerman K.F. Handbook of anatomical models for radiation dosimetry; 2009. (Boca Raton, FL: Taylor & Francis)