NUKLEONIKA 2013;58(4):519–525

ORIGINAL PAPER

A Whole-Body Spectrometer (WBS) at the Institute of Nuclear Physics, Kraków – design and results for Polish citizens visiting Japan during the Fukushima accident

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Abstract. The first Polish whole-body spectrometer (WBS) with scintillation detectors was constructed in Łódź in the early sixties of the last century and was operating there for more than 30 years. In 2008, the 19th century steel shield of this instrument was transported from Łódź to Kraków, where it was re-equipped with a modern gamma spectrometric system. Design and construction of this modernized spectrometer is presented along with the results for in-body contamination measurements of four Polish inhabitants who returned to Poland from Japan after the Fukushima accident compared with the results for typical Polish inhabitants, the volunteers from the Institute of Nuclear Physics (IFJ, Kraków) workers. Although, a clear signal from the Fukushima fallout was noticed for three of four persons who returned from Japan, the calculated doses were negligible. No traces of Fukushima-originating radionuclides were noticed for the examined people who have not traveled to Japan.

Key words: whole-body spectrometry (WBS) • Fukushima • body burden • gamma spectrometry • doses

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Received: 30 January 2013
Accepted: 10 July 2013

Introduction

The whole-body counting is a well known technique used for the determination of body burden with gamma emitters. It was developed during the cold war era with the aim of studing the body burden of workers of nuclear industry. Later, it was successfully applied for screening studies of radioactive body burden in general public as well. Although the design is basically only for the detection of gamma emitters, it is interesting that with a much worse detection limit it can be even used for the determination of body content of pure beta emitters, especially those with a high maximum energy of beta radiation (like ^{90}Y, for example) using secondary gamma rays (bremsstrahlung).

The first Polish whole-body counter was developed in the mid-sixties of the last century in Łódź and for more than 30 years was used for mainly radiobiological research of different teams led by Prof. J. Liniecki. Actually, it soon became a whole-body spectrometer (not "counter") since a large NaI spectrometric system was installed as detector system. Later, it was accompanied by a second scintillation detector, which was moving from head to foots, what made it possible to scan intensity of radiation along the human body in order to detect the activity distribution in organs. Another Polish whole-body system was established also many years ago at Świerk, working for the staff of reactor centre [6].

One of the peculiarities of the shield of the whole-body spectrometer (WBS) in Łódź was its unusual material. It was made of XIX century steel plates obtained from scrapped old industrial installation like huge steam boilers. This was done intentionally to get material free of traces of ^{60}Co commonly present in all modern steels. After dismounting, in pieces (but still more than 100 kg each) this shield and one large scintillation detector were moved in 2008 from Łódź to Kraków, to the Institute of Nuclear Physics of Polish Academy of Sciences (IFJ PAN). During the following two and half years, it was installed here and re-equipped with a modern high resolution gamma spectrometric system.

The WBS at this Institute is planned to be used for typical purposes like monitoring of intakes of radioisotopes by workers who deal with radionuclides, not only the workers of IFJ PAN but, for example, also the medical staff who works in domain of nuclear medicine, which nowadays develops rapidly, or workers who are exposed to various activation field of scattered particles (for example cyclotron staff). It can also be used in case of any incidents or accidents in which radioactive materials could be released. Eventually, it can also be used for scanning of general population for caesium or other radionuclides body burden. We plan also to do special calibration for a bremsstrahlung registration technique for ^{90}Sr-^{90}Y. Besides, the whole-body measurements can be applied for dedicated measurements of ^{131}I in the thyroid gland. To do the later we applied a special small calibration source of appropriate shape, placed inside a phantom of the neck.

The system of our WBS reached operational status in February 2011. This appeared just in time since on 11 March 2011 the Fukushima accident happened and this gave us the opportunity to do the described below study. Four Polish inhabitants who returned to Poland from Japan after the Fukushima accident were measured at the end of March and April 2011. Independently, the measurements of volunteers of our team were done to register "Polish population background" spectra.

Method

The whole-body spectrometer is a fully shielded spectrometer (Figs. 1–3). As was mentioned, the shield itself was constructed in 1963 in Łódź [4]. It was a box-like shield (2 × 1.3 × 1.2 m of inner, shielded volume) made of 19th century steel. The total shield wall thickness is

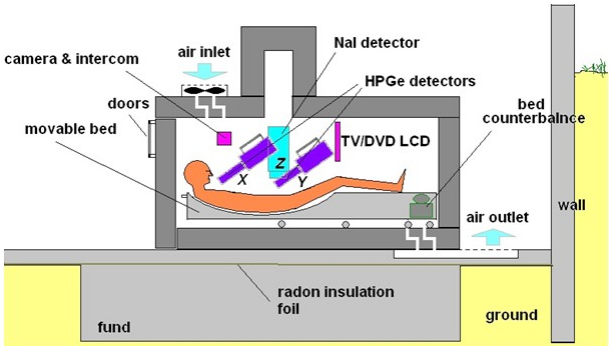

Fig. 1. A scheme of construction of whole-body spectrometer in the IFJ PAN, Kraków applied in present measurement (X, Y, Z – detector codes used in text).

Fig. 2. A general view of the spectrometer with closed doors. Visible are also: a dewar of LN_2 refilling the system (left) and NIM electronics modules (right), ventilation system (on the top of the shield).

17 cm and the whole shield mass is 18 t. Inside the shield at all six walls we have recently added a 3 mm copper lining. In fact, this part of shield is added mostly due to aesthetic reasons, the bare copper surface is much nicer to eyes than the almost black steel. There are movable heavy (2 t) doors.

After moving the shield to Kraków, it was installed in a freshly prepared special room at the basement level on a separate concrete foundation. A special attention was paid to provide gas insulation from the ground below the room to reduce radon inflow – a foil membrane

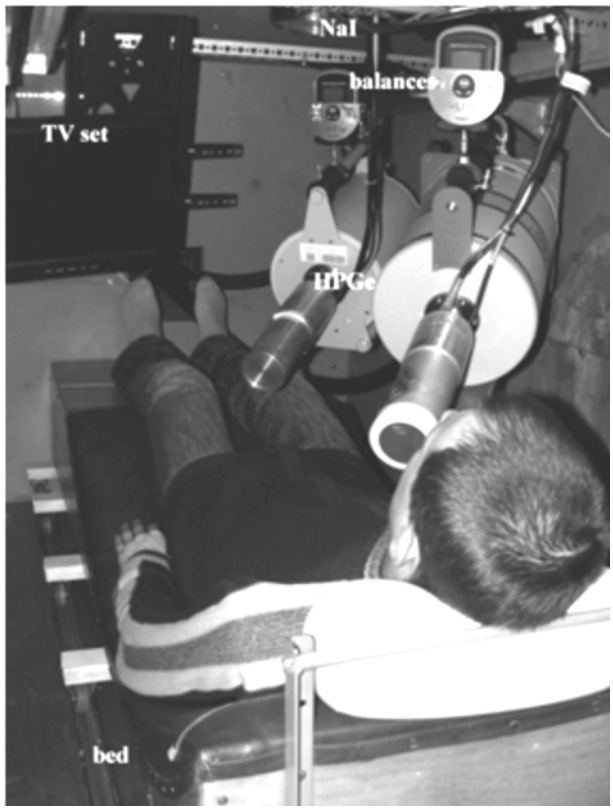

Fig. 3. A view of inside of the spectrometer prepared for measurement with a patient lying on the bed, visible: are the bed, two germanium detectors, the balances on the struts and TV. The NaI detector is moved upward, into the shield and only part of it can be noticed on the top of the picture.

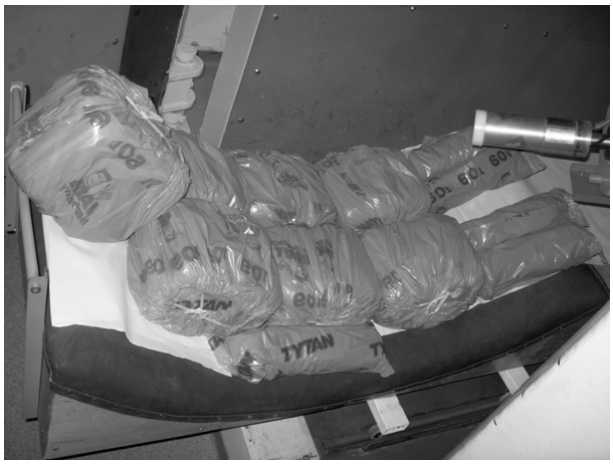

Fig. 4. A calibration phantom SICa-1 during preparation for measurements in the whole-body spectrometer, lying on the bed in extended position.

was added on the floor. The bed has a steel frame and a plywood overlay. During measurement, the patient's body lies on a soft, comfortable lining which covers the main part of the bed. At the foot of the bed a counterbalance is mounted to assure a stable and horizontal position of the bed during taking place by the patient. A new, modern spectrometric system was installed within the shield. It consist of two Ortec HPGe (high purity germanium) spectrometers (30% relative efficiency each) and a 5 inch diameter NaI(Tl) scintillation spectrometer which remained as a part of the previous system. This scintillation detector can be removed upward by the operator. Germanium detectors are mounted in a 7 L, brand new portable dewar-cryostat. Each detector is suspended on two struts. There are simple electronic balances in their front suspension strut to monitor the LN_2 levels. The pneumatic LN_2 refilling system is installed. The electronics are NIM modules from Canberra and spectra are collected using Canberra Genie 2000 acquisition software. The spectrometer shield is equipped with a ventilation system, LED light and a monitoring camera, with intercom to provide contact with the patient. Finally, it contains also a LCD TV/DVD set to amuse patient during spectra collection.

Despite the fact that the whole spectrometer is localized in a room at the basement level, due to a modern ground insulation system the radon level measured during wintertime over a weekend by means of an AlphaGuard ionizing chamber was, on average, at the level of 40 Bq/m^3. The spectrometer was turned into operation in February 2011, a month before the Fukushima accident.

Two calibration geometries were proposed. One is just for thyroid measurements, another one is for the whole-body spectrometry. The thyroid like geometry was initially approximated by a cylindrical, 140 ml volumetric source localized in a place where the thyroid gland is expected to be within the examined person. However, since it appeared not correct, after about one year a recalibration was done using a thyroid shape phantom filled with a known amount of ^{131}I. All presented here results for ^{131}I were calculated using this calibration, and are significantly smaller than our initial results, which were already presented unofficially during seminars, etc. The main calibration source – Source for Improvised Calibration (SICa-1, Fig. 4) for the whole-body counting was made of a set of 7 polyethylene cubic tanks of 5 L volume, six of which form a human thorax and an abdomen-like shape and the seventh is in the place of head. Additionally, six 1.5 L cylindrical bottles are used, four of them are pretending arms and hands, two other – the upper part of legs. All those containers were filled with the same liquid, a multi-isotopic source which includes ^{60}Co, ^{137}Cs, ^{40}K, ^{133}Ba and ^{241}Am solution. The total activity of the phantom is on at level of 10 kBq. This liquid source was solidified using gelatin with a small amount of formaldehyde added.

Results

The Fukushima accident, which followed the earthquake and tsunami of 11 March 2011, gave the first opportunity to use our WBS. During March and April 2011, four Polish inhabitants who traveled back from Japan and who were exposed there to Fukushima fallout were the subject of measurements. For comparison, Polish residents, workers of IFJ PAN who did not travel to Japan were measured. Basic data on the date of measurement are presented in Table 1. The results for the whole-body counting of all those persons are presented in Table 2. All results were calculated for the day of measurement. The uncertainties presented in Table 2 are 1 sigma counting statistic only, whereas the minimum detectable activity (MDA) is calculated with a restricted Curie formula [2] which is exactly equivalent to the IAEA 1996 recommendation for whole-body measurements [3]. We decided to present in Table 2 each result, which with added 1 sigma uncertainty is not smaller than the formal MDA value.

Besides, the spectrometer was used also for a qualitative activity measurements of a jacket of a person being exposed to the fallout and soaked by rain in Tokyo.

Table 1. Basic data on measurements of examined persons

Code	Sex	Body mass (kg)	Date of measurement	Arrival to Japan	Departure from Japan	Place of residence in Japan
P1	W	55	2011-03-24	2011-03-10	2011-03-16	Tokyo
P6	M	68	2011-04-07	2011-02-22	2011-03-21	Tsukuba
P7	M	70	2011-04-19	2011-03-02	2011-03-14	Tokai
P8	W	56	2011-04-26	2010-12-01	2011-03-20	Tsukuba
P2[a]	W	63	2011-03-24	–	–	No visiting Japan
P3	W	83	2011-03-24	–	–	
P4	M	65	2011-03-25	–	–	
P5	M	60	2011-03-28	–	–	

[a] Measurement just after flight from the USA to Poland.

Table 2. Results for whole-body measurements

No.	Patient code	Isotope	Detector	Activity, A (Bq)	MDA	^{134}Cs / ^{137}Cs	
						Detector X	Detector Y
1	P1	^{134}Cs	X	27 ± 5	(18)	1.48 ± 0.95	–
			Y	<*	(41)		
		^{137}Cs	X	18 ± 11	(29)		
			Y	36 ± 19	(48)		
		^{40}K	X	2330 ± 440	(546)		
			Y	2410 ± 440	(866)		
2	P6	^{134}Cs	X	126 ± 11	(23)	1.03 ± 0.16	0.94 ± 0.29
			Y	103 ± 20	(50)		
		^{137}Cs	X	122 ± 16	(31)		
			Y	110 ± 27	(75)		
		^{40}K	X	4180 ± 300	(575)		
			Y	3860 ± 360	(684)		
3	P7	^{134}Cs	X	<	(20)	–	–
			Y	<	(28)		
		^{137}Cs	X	25 ± 13	(34)		
			Y	25 ± 17	(45)		
		^{40}K	X	3950 ± 300	(542)		
			Y	3640 ± 370	(731)		
4	P8	^{134}Cs	X	36 ± 6	(18)	1.13 ± 0.49	1.03 ± 0.34
			Y	69 ± 10	(32)		
		^{137}Cs	X	32 ± 13	(34)		
			Y	67 ± 20	(48)		
		^{40}K	X	2310 ± 450	(534)		
			Y	2650 ± 480	(697)		
5	P2	^{134}Cs	X	<	(26)	–	–
			Y	<	(25)		
		^{137}Cs	X	<	(26)		
			Y	<	(38)		
		^{40}K	X	2870 ± 380	(584)		
			Y	3180 ± 410	(721)		
6	P3	^{134}Cs	X	<	(21)	–	–
			Y	<	(27)		
		^{137}Cs	X	<	(31)		
			Y	<	(35)		
		^{40}K	X	2930 ± 370	(542)		
			Y	3190 ± 410	(704)		
7	P4	^{134}Cs	X	<	(29)	–	–
			Y	<	(30)		
		^{137}Cs	X	<	(32)		
			Y	<	(43)		
		^{40}K	X	3530 ± 320	(570)		
			Y	4090 ± 330	(730)		
8	P5	^{134}Cs	X	<	(41)	–	–
			Y	<	(47)		
		^{137}Cs	X	58 ± 19	(44)		
			Y	<	(70)		
		^{40}K	X	3400 ± 240	(837)		
			Y	3060 ± 300	(1098)		

*< – denotes "below MDA" given then in brackets.

Obtained spectrum is presented in Fig. 5. This spectrum brings information on gamma emitting isotopes, which were present in the fresh Fukushima fallout in Japan in the first days of accident. Beside ^{131}I, ^{132}I and ^{134}Cs,^{137}Cs, one can notice ^{129m}Te, ^{129}Te, ^{132}Te and ^{136}Cs. However, during the whole-body measurements only ^{131}I, ^{134}Cs, ^{137}Cs and natural ^{40}K were found.

The first person (code P1) who was measured was a young woman, a fashion model, who was expected to take a part in a show in Tokyo which was canceled and she returned home on 16 March. She was measured on 24 March 2011, so at least 8 days after the end of exposition. The measurement was lasting for 1 h. Spectra from all three detectors are presented in Figs. 6a–6c.

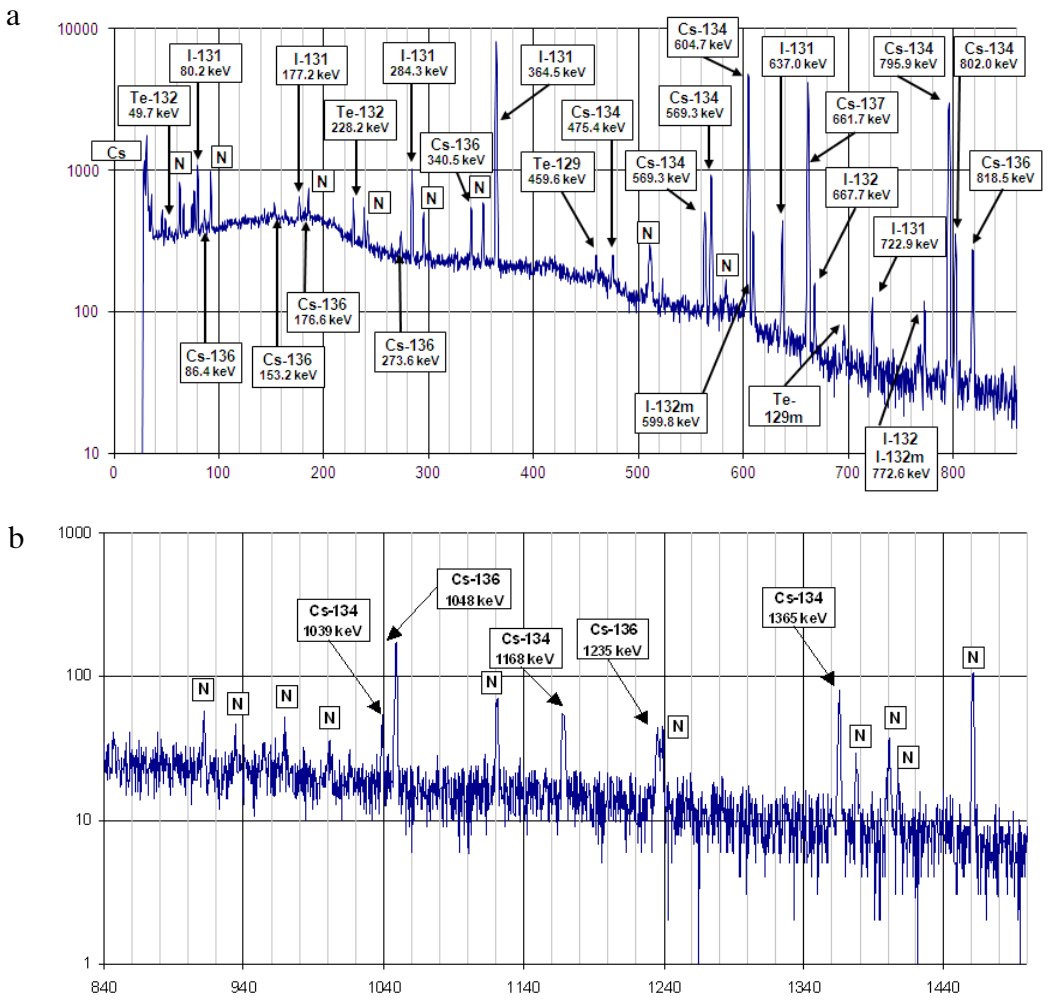

Fig. 5. Gamma spectrum of the Fukushima fallout deposited on a jacket exposed to rain in Tokyo, measured in a Whole-Body Spectrometer in Kraków on 5 April 2011. Described are gamma lines from fallout, peaks marked as "N" are gamma lines of natural isotopes present in the background of spectrometer.

A comparison of the spectra from both the germanium detectors (X and Y) and NaI detector (Z) clearly indicates that despite much higher efficiency the NaI detector is not suitable for whole-body measurements of such radioactive traces. Thus, in the next measurements it was moved upward into the shield. Beside a clear signal from ^{131}I, the traces of ^{134}Cs and ^{137}Cs in the range of MDA were present in the spectrum of detector X, situated above the upper part of the body. This suggests, that an important fraction of caesium was still present in the lungs during measurement, not distributed yet within other soft tissues.

During March and April 2011, three other persons were measured. Two of them were working in the filed of high energy nuclear physics. One was a physicist (P7), the second one was an electronic engineer (P6) and the third one (P8) was a chemist. All of them were on duty trips to Japan in time of the accident. They worked at Tokai or Tsukuba and all visited Tokyo to fly back to Poland. Obtained gamma ray spectra for three of the four the persons reveal traces of both ^{134}Cs and ^{137}Cs, the spectra for the fourth one only the ^{137}Cs. The highest results for radiocaesium were at a level of 120 Bq for a man (P6), who left Japan later than the others, on 21 March 2011. In this case for both caesium isotopes the detector X shows slightly (about 10%) higher activities than detector Y, what might also suggest partial presence of caesium aerosols in lungs. The ratio of ^{134}Cs to ^{137}Cs was close to 1 indicating Fukushima as a dominant origin of radiocaesium. On the contrary, in the case of person P8 (woman) detector Y (above bottom part of the body) registered two fold higher activities for both caesium isotopes than that of detector X. She was measured as the last one, on 26 April 2011, and likely the lungs were already free of radiocaesium. This should not be a result of radiocaesium content in urine collected in bladder, since all persons were asked to visit toilet before measurements.

Results for both germanium detectors for ^{40}K gave similar results for each person, what one might expect since potassium should be distributed rather evenly within soft tissues of human body. They range from 2310 ± 450 Bq (P8, detector X) to 4180 ± 300 Bq (P6, detector X). The examined Polish inhabitants who did not travel to Japan, revealed similar levels of ^{40}K, but did not reveal any traces of Fukushima related radioisotopes like ^{131}I or ^{134}Cs.

Table 3 presents the results for ^{131}I calculated for both HPGe detectors using thyroid gland geometry calculated for the day of measurement. The ^{131}I was detected mostly by the germanium detector which was above the upper part of the body (detector X).

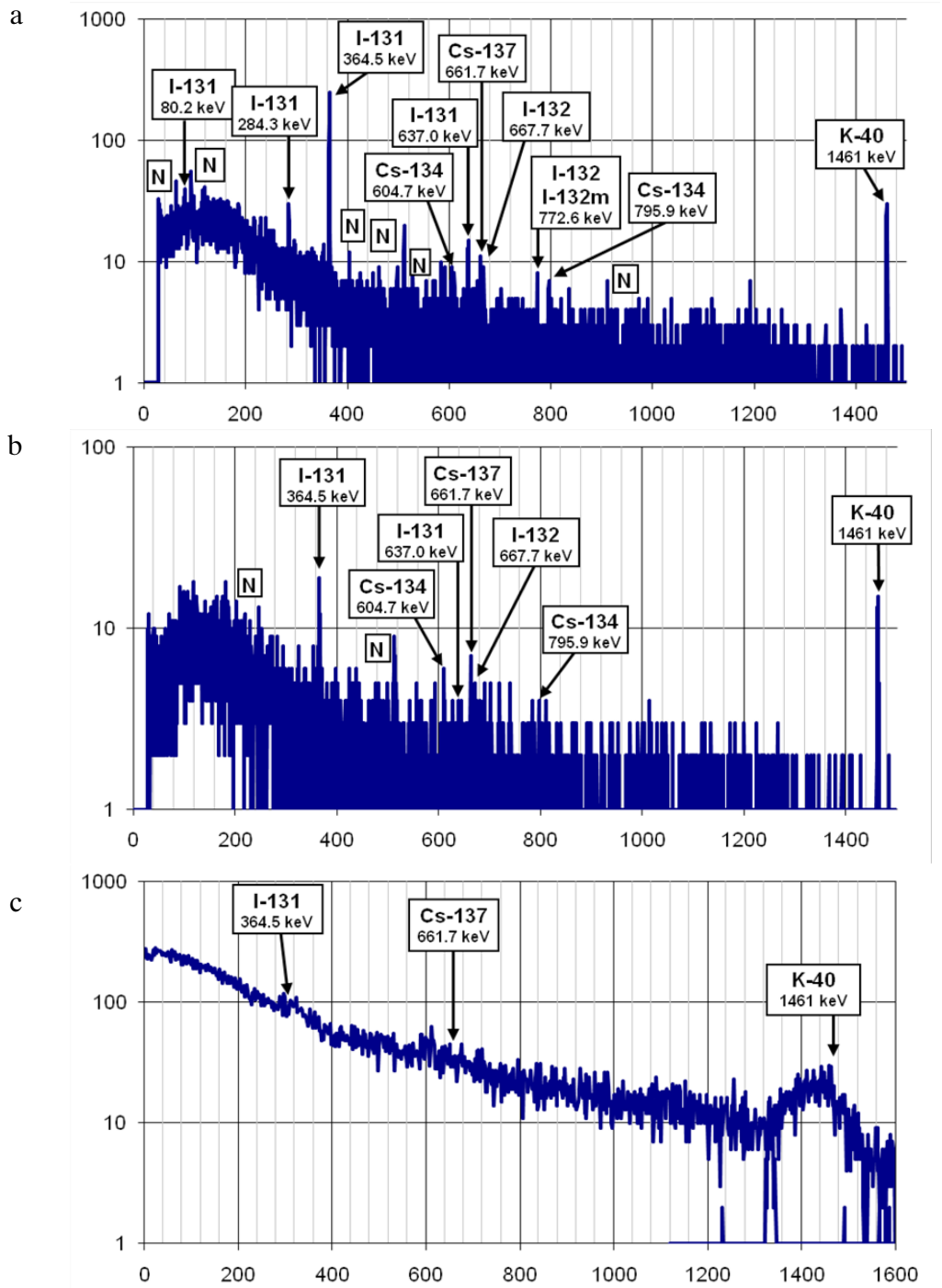

Fig. 6. Gamma spectra of the patient P1 obtained from different detectors during the same measurement, from above: detector HPGe above the upper part of body (X), detector HPGe on the lower part of abdomen (detector Y) and NaI detector (Z).

This was expected since the iodine is accumulated in the thyroid gland. The results for more remote from neck detector Y are always much higher than those for detector X. Those results are obviously false (since detector Y was calibrated for the presence of ^{131}I only within thyroid gland) but they are presented to illustrate that radioiodine was present also in other, closer to detector Y organs or tissues situated in the lower part of the body. Obviously, presented activities for detector Y do not have any physical meanings beside just the information that ^{131}I is observed somewhere else than in thyroid.

The highest measured ^{131}I activity in the thyroid gland by detector X was equal to 73 ± 11 Bq (for the day of measurement), for person P1. However, since all results are given for the day of measurements, the original activities for person P6 had to be much higher than that for P1, who was measured two weeks earlier. After taking into account the time between presumable main exposition and measurement it gives approximately up to 540 ± 80 Bq of the initial activity of ^{131}I for this person.

Dose estimation

The doses were calculated from the body burden in the most conservative approach, using the highest

Table 3. Results for ^{131}I measurements using calibration for the thyroid gland

No.	Patient code	Detector	Activity, A (Bq)	MDA
1	P1	X	73 ± 11	(3.4)
		Y	204 ± 34	(80)
2	P6	X	50.1 ± 7.2	(2.7)
		Y	367 ± 41	(66)
3	P7	X	–	(2.3)
		Y	–	(47)
4	P8	X	2.48 ± 0.72	(1.7)
		Y	–	(45)
5	P2	X	–	(2.7)
		Y	–	(45)
6	P3	X	–	(2.8)
		Y	–	(45)
7	P4	X	–	(2.8)
		Y	–	(52)
8	P5	X	–	(4.0)
		Y	–	(73)

Table 4. Estimated effective dose equivalent H_{50} for the examined person due to the observed activities of artificial nuclides from the Fukushima fallout

No.	Patient code	Isotope	H_{50} (μSv)
1	P1	^{131}I	3.1 ± 0.5
		^{134}Cs	0.5 ± 0.1
		^{137}Cs	1.4 ± 0. 8
2	P6	^{131}I	8.6 ± 1.2
		^{134}Cs	2.6 ± 0.2
		^{137}Cs	4.8 ± 0.6
3	P7	^{131}I	<1.3
		^{134}Cs	<0.4
		^{137}Cs	<1.3
4	P8	^{131}I	2.8 ± 0.8
		^{134}Cs	1.4 ± 0.2
		^{137}Cs	2.6 ± 0.8

possible dose conversion factors [1]. At our simplified approximation, the observed activities were assumed as a result of a single intake on 14 March 2011 (as the earliest possible moment, for reason of conservative approach) and thus especially ^{131}I should be corrected back to the date of 14 March 2011. This correction was done with the assumed effective biological half-life time of ^{131}I equal to 7.05 days [5]. For both caesium isotopes only physical half-life was taken into consideration in activity corrections, however those corrections were not significant. The result of the doses assessments for all those persons are set in Table 4. Uncertainties presented there are only those resulting from counting statistics. The systematic uncertainties which may appear due to the too conservative approach are presumable on the level of 50%. The effective dose equivalent H_{50} does not exceeds the level of 10 μSv in any of the cases presented here, however it is interesting that the calculated values of H_{50} from radiocaesium are comparable (as sum for both isotopes) with those for ^{131}I. It can be concluded that the estimated doses are very small and the risk is therefore negligible.

Conclusions

The beginning of operation of our WBS system coincidence with the Fukushima accident, what gave us the opportunity to measure body burden for few inhabitants of Poland who were visiting Japan during the time of accident. Contamination observed in the human bodies resulted in very small doses making no risk. No influence of the Fukushima accident was observed for any of the examined person who did not stay in Japan.

Acknowledgment. The authors want to express their gratitude to Prof. J. Liniecki, J. Niewodniczański, M. Jeżabek and P. Olko for initiative, openness and support for the idea of movement of spectrometer shield to Kraków. Prof. I. Croudace and Dr P. Gaca of the National Oceanic Center (Southampton, UK) are warmly acknowledged for their help with the detector system. We are also very thankful to Dr K. Kozak from our Institute for radon measurements and to Dr G. Krajewska from the Central Laboratory for Radiation Protection, Warsaw, for a loan of thyroid gland phantom. Last but not least, we are also very grateful to all engineers and technicians for their hard work during dismounting, transport and reconstruction of the shield.

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