4π PLASTIC-SCINTILLATOR WHOLE-BODY COUNTER FOR CLINICAL USE

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Liège University has recently set up a whole-body counter for clinical use. The main proposed uses are the measurement of body potassium using ^{40}K and metabolic studies using single tracers. High sensitivity is required to reduce the counting time, and good geometry is necessary to avoid complex calibration and errors arising from various distributions of isotopes within the body (*1*). A 4π organic scintillator was chosen despite the relatively poor energy resolution provided by this kind of detector. This is not a great shortcoming in clinical whole-body counting because the tracer is always a well-known isotope. As far as we are aware, the Liège 4π plastic scintillator counter is the only one of its kind in Europe and possibly in the world.

DESCRIPTION OF THE COUNTER

The Liège whole-body counter was built by Nuclear Entreprises Ltd., Edinburgh. The counter consists of three logic parts: shielding, detector and electronics. Shielding is provided by a steel room entirely surrounding the detector. The steel was salvaged from a pre-nuclear-age battleship and is 15 cm thick. The front door has an opening allowing the patient to be introduced on a stretcher running on guide rails. The detector has the form of an annulus and is made up of six independent sections (three upper and three lower). Scintillator thickness is 17.5 cm, length is 200 cm and volume is 692 liters. The inner diameter of 47.5 cm is adequate for admitting practically all persons. To each of the six sections are connected three photomultiplier tubes, the total scintillator contact area being 942 cm^2. The 18 photomultiplier tubes have a total cathode area amounting to 11% of the total outer surface area of the scintillator. The electronics comprise mainly a three-channel analyzer, sufficient for routine work. For calibration work a 400-channel analyzer is used. Precautions taken against claustophobic hazards include music broadcasting.

PERFORMANCES

Stability. A fundamental requirement of a spectrometer with relatively poor energy resolution is high stability since it is not possible to check the position of reference radioisotope photopeaks. Drift can only be allowed within very strict limits. The problem is complicated by the large number of photomultiplier tubes, each of which has a response curve peculiar to itself. Balancing the photomultiplier-tube gains with high voltage was, of course, a very laborious task. Thereafter, we checked stability over a period of several months by measuring background and radioactive sources under various conditions. In the energy range above 0.25 MeV, the drift, if any, was always less than 1%. We did not observe any background variation with weather conditions over a period of 1 year.

Background. For measuring very low activities, background reduction is of primary importance. Figure 1 shows the shielding effectiveness: a tenfold reduction in background occurs in the median energy range. An anticoincidence circuit reduces the contributions at higher energies. Figure 2 shows the

Received Nov. 4, 1968; revision accepted July 11, 1969.

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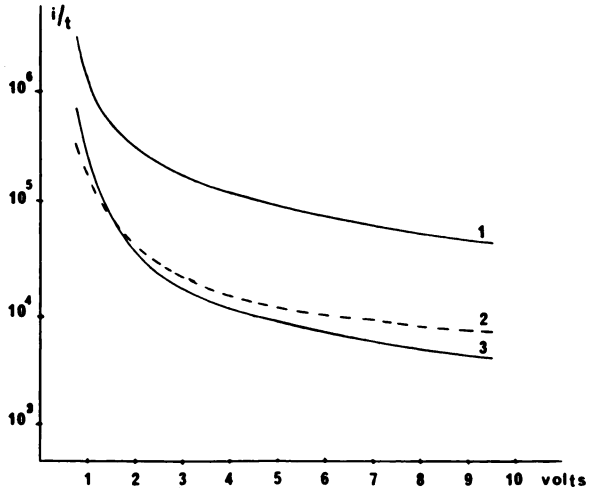

FIG. 1. Shielding effectiveness. Background (1) without shielding; (2) with shielding but without anticoincidence circuit; and (3) with shielding and with anticoincidence circuit. Ordinate gives impulses vs time; numerical values are in cpm/MeV.

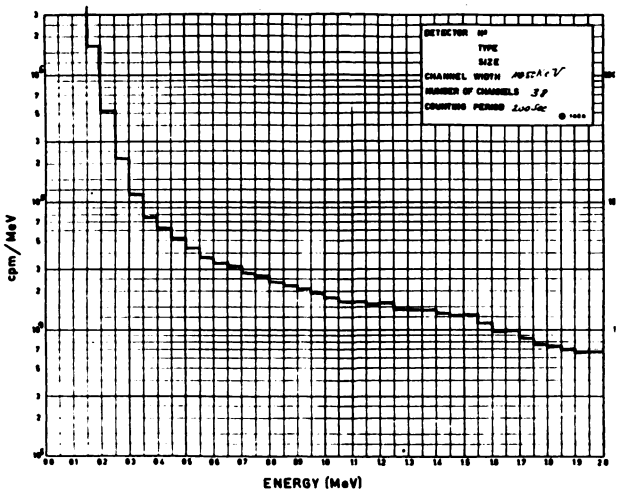

FIG. 2. Background spectrum (with shielding and anticoincidence circuit). Channel width is 50 keV; counting time is 200 sec/channel.

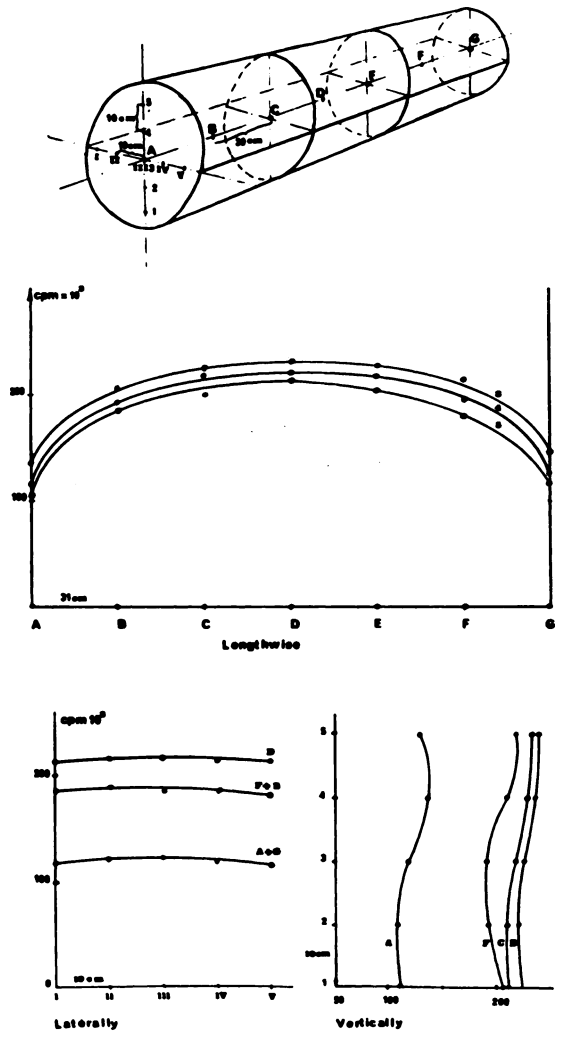

FIG. 3. Geometry factor in response of counter. Upper part of graph shows positioning of ^{86}Rb source along three axes in counting chamber. Lower part gives values obtained in each position.

background spectrum measured with a 50-keV window; its shape is quite different from that produced by a crystal scintillator. The high values in the lower energy range are mainly due to dark current from the 18 photomultiplier tubes. Within the 0.2–2.0-MeV range, the background counting rate is 77,000 cpm or 1.9 counts/sec/liter of scintillator. This figure compares favorably with other organic detectors (*2*).

Isotropy. The 4π geometry was chosen to obtain uniform results, whatever the isotope distribution in the body. The requirement for an "isotropic" response is only approximately satisfied and must be experimentally confirmed. The response of the counter to a 0.1-μCi ^{86}Rb source was measured for 63 positions within the counting chamber. Figure 3 shows the results. The positioning of the source inside the counting chamber can be seen, with the values obtained along the three axes. Laterally, the uniformity is practically perfect; vertically, the response is slightly distorted in the bottom part probably because of a shielding effect produced by the stretcher support. Horizontally, there is a slight efficiency impairment at both ends as was anticipated (*3*). We can conclude that the response isotropy is very satisfactory, even for a point source.

Resolution. In organic scintillators Compton scattering is the main gamma-ray absorption process. It follows that such gamma-ray spectra have peculiar properties.

1. The Compton edge falls at an energy lower than that of the photopeak by the amount of energy carried off by gamma rays scattered at 180 deg as indicated by

$$E_\gamma' = E_\gamma - \frac{E_\gamma}{1 - \frac{2E_\gamma}{mc^2}} \qquad (1)$$

   in which E_γ is photopeak energy and E_γ' is Compton-edge energy.
2. The phenomenon is a continuous one with no precise boundary between Compton effect and backscattering,
3. Consequently, the "peaks" shown in graphs are asymmetrical.

Therefore, instead of "resolution," the term "half resolution," according to Bird's definition (*4*) is used. The "half resolutions" were measured as follows:

1. Point sources were placed at the geometrical center of the counter,
2. Source activity was about 37,000 dis/sec (1 μCi),
3. Spectrum was scanned using a 50-keV wide channel,

TABLE 1. MEASUREMENTS OF SOME REFERENCE RADIONUCLIDES

Isotope	E_γ (keV)	E_γ' (keV)	Voltage (volts)	Resolution % (HWHM)	Peak-to valley
^{51}Cr	323	180	0.7	80	—
^{137}Cs	662	478	1.9	67	1.05
^{54}Mn	840	644	2.5	61	1.05
^{86}Rb	1,080	874	3.6	50	1.13
^{65}Zn	1,110	902	3.8	46	1.14
^{40}K	1,460	1,242	5.2	39	1.21
^{42}K	1,520	1,301	5.4	42	1.31

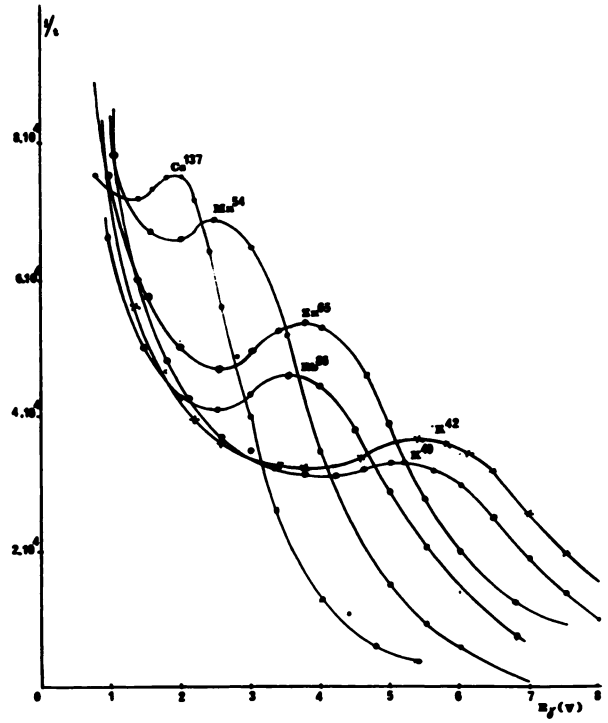

FIG. 4. Spectra (minus background) of some radioisotopes emitting gamma rays with single energy.

4. Counting time was that required to obtain 10,000 counts with background subtracted.

Seven isotopes emitting gamma rays with a single energy were studied: ^{42}K, ^{40}K, ^{65}Zn, ^{86}Rb, ^{54}Mn, ^{137}Cs and ^{51}Cr. The results of the measurements appear in Table 1 and Fig. 4. The constancy of the Compton-edge position on the energy scale allows calibration in terms of energy in accordance with Eq. 1. The relatively poor energy resolution, as foreseen, varies with gamma-ray energy in the manner found by Andrews (*5*) (Fig. 5).

Isotopes emitting gamma rays with two or more energies were also studied. The problem is the same for a combination of two or several monoenergetic gamma-ray sources as for isotopes with several gamma rays; the low resolution allows discrimination only in certain cases. Figure 6 shows spectra for several combinations:

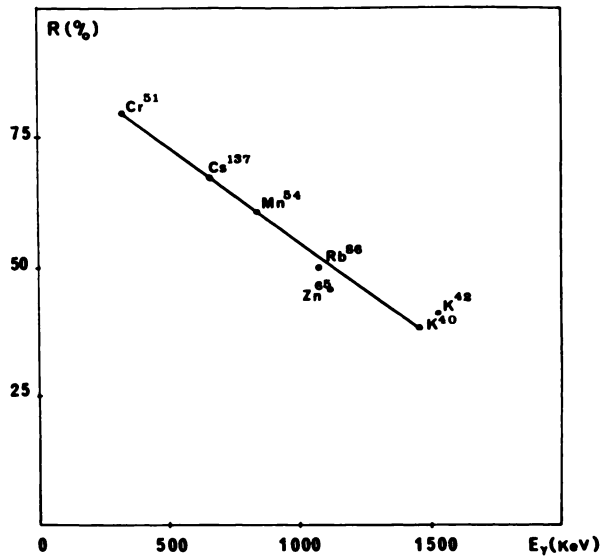

FIG. 5. Relationship between half resolution in percent, R (%), and energies of gamma rays in keV ($E\gamma$).

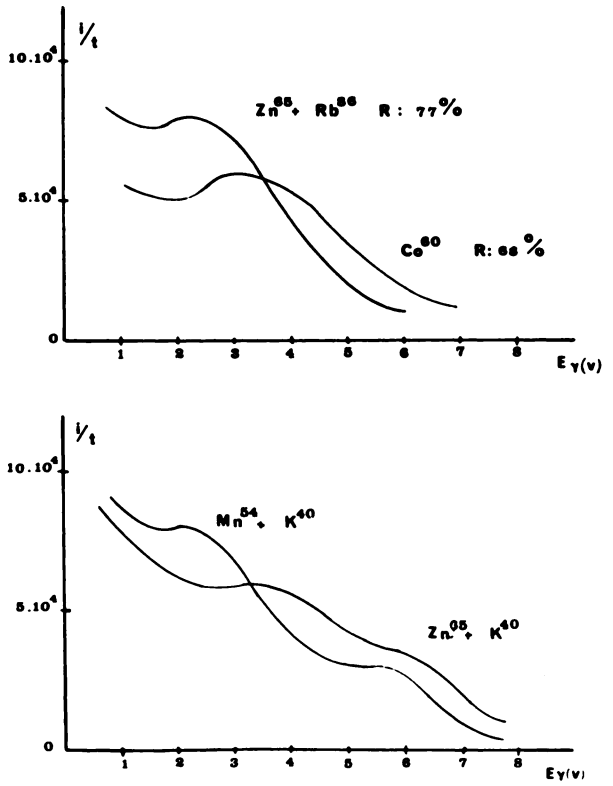

FIG. 6. Spectra (minus background) of isotope (^{60}Co) emitting two gamma rays or combinations of two radionuclides emitting single-energy gamma rays. See text for explanation of curves.

1. Two gamma rays separated by less than 0.2 MeV are unresolved and only one peak appears with a resolution impaired according to the above relationship.

   Examples: ^{60}Co, $^{65}Zn + ^{86}Rb$

TABLE 2. EFFICIENCY AND FIGURE OF MERIT FOR SOME RADIOISOTOPES

Energy range (volts)	^{51}Cr		^{131}I		^{137}Cs		^{54}Mn		^{22}Na		^{86}Rb	
	Eff.(%)	FM	Eff.(%)	FM	Eff.(%)	FM	Eff.(%)	FM	Eff.(%)	FM	Eff.(%)	FM
0.5–1	24.7	2,120	20.8	7,516	8.2	186	7.0	186	6.8	166	6.4	362
1 –2	16.0	5,285	14.9	18,885	17.4	4,461	11.0	2,719	10.5	2,406	8.3	3,550
2 –3	1.7	227	3.1	2,701	15.0	5,965	10.0	4,698	7.5	2,650	6.2	4,336
3 –4	0.2	41	0.7	264	6.5	2,175	8.5	3,953	5.1	1,825	7.5	6,939
4 –5	—	—	0.2	—	2.2	449	4.2	1,572	4.5	1,651	6.7	5,455
5 –6	—	—	—	—	0.8	88	2.5	826	4.0	1,617	3.5	2,561
6 –7	—	—	—	—	0.2	—	0.8	135	3.0	1,210	1.5	861
7 –8	—	—	—	—	—	—	0.3	41	2.0	700	0.8	403
8 –9	—	—	—	—	—	—	—	—	1.4	526	0.4	148
	42.6		39.7		50.3		44.3		44.8		41.3	
	^{65}Zn		^{59}Fe		^{60}Co		^{40}K		^{42}K		^{24}Na	
0.5–1	3.2	20	9.9	324	4.2	71	10.0	138	10.2	788	16.8	9,169
1 –2	6.4	602	10.6	1,508	5.2	797	13.6	2,248	9.6	3,896	5.8	4,417
2 –3	5.3	961	8.5	2,194	4.7	1,428	5.0	814	6.0	3,385	4.0	4,876
3 –4	5.6	1,358	9.6	3,080	5.3	2,109	4.3	793	5.4	3,420	3.9	6,176
4 –5	5.6	1,408	9.8	3,380	6.0	2,774	4.0	864	5.6	4,000	4.1	7,530
5 –6	3.5	875	7.0	2,453	5.5	2,688	4.1	1,075	6.3	4,987	4.2	8,658
6 –7	1.8	374	3.9	1,210	4.0	1,932	4.0	1,210	5.7	4,710	3.5	7,402
7 –8	2.1	563	2.2	600	2.9	1,411	3.4	1,045	3.9	3,112	2.7	5,948
8 –9	1.9	546	1.3	306	2.2	1,071	2.5	704	2.3	1,745	1.4	5,477
	35.4		62.8		40.0		50.9		45.0		46.4	

TABLE 3. SENSITIVITY OF MEASUREMENTS

Isotopes	Low level (volts)	Window (volts)	Efficiency (%)	Activity (nCi) giving 10,000 cpm	Fraction of ICRP MPBB measured in 1-min count with 5% accuracy
^{51}Cr	0.5	1.5	40.7	143.0	1.8×10^{-4}
^{131}I	0.5	2.5	36.4	14.3	4.7×10^{-5}
^{137}Cs	1.0	2.0	32.4	18.0	6.0×10^{-4}
^{54}Mn	1.0	4.0	33.7	14.3	7.3×10^{-5}
^{22}Na	1.0	5.0	31.6	15.6	1.6×10^{-5}
^{86}Rb	1.0	5.0	32.2	180.8	6.0×10^{-5}
^{65}Zn	1.0	5.0	26.4	38.3	6.3×10^{-4}
^{59}Fe	2.0	5.0	38.8	17.0	8.6×10^{-4}
^{60}Co	2.0	5.0	25.5	19.3	1.9×10^{-5}
^{40}K	3.0	5.0	19.8	—	—
^{42}K	3.0	5.0	26.9	104.2	1.0×10^{-5}
^{24}Na	4.0	5.0	16.8	29.6	4.3×10^{-5}

2. Two gamma rays separated by more than 0.6 MeV give two distinct Compton edges.
   Example: $^{40}K + ^{54}Mn$
3. Two gamma rays separated by more than 0.2 MeV but less than 0.6 MeV are partially resolved according to energy in the interval.
   Example: $^{40}K + ^{65}Zn$

Efficiency. Efficiency estimation is the main point of the performance study. The problem is a complex one because efficiency must be strictly defined with regard to a particular gamma-ray energy, a standardized geometry and defined spectrometric adjustments. This last requirement is the most important since one measures the Compton effect where several successive interactions may take place for one photon.

We have estimated efficiency using 0.1 μCi (3,700 dis/sec) sources at the geometrical center of the counter. The energy spectrum was scanned using a 0.1-volt-wide (250-keV) channel. The output percentage and figures of merit were tabulated for each energy range. The figure of merit (FM) (6) was calculated for a counting time of 200 sec by the formula:

$$FM = \frac{S^2}{S + 2B} \qquad (2)$$

in which S is output minus background and B is background.

Table 2 gives the results for 12 isotopes currently used in medical practice. Consideration of available counting rate and the figures of merit enables the most appropriate spectrometric condition to be chosen for each isotope.

Table 3 shows these conditions and the overall efficiency for each istope, the activity to produce 10,000 cpm and the minute portion of ICRP maximum permissible body burden (MPBB) that can be measured in a 1-min count (7). It appears that efficiency is very high and that the counting sensitivity permits the measurement of activities 10^3–10^4 times lower than maximum permissible body burden.

Efficiency. Linearity versus intensity was checked over a range of gamma-ray energies using isotopes which were different with respect to gamma-ray emission energies, number of different lines emitted and emission percentages. The isotopes were ^{51}Cr, ^{137}Cs, ^{131}I, ^{59}Fe, ^{22}Na and ^{40}K. The yield is linear within a dose range of 10^3 except at the beginning of the curve (Fig. 7).

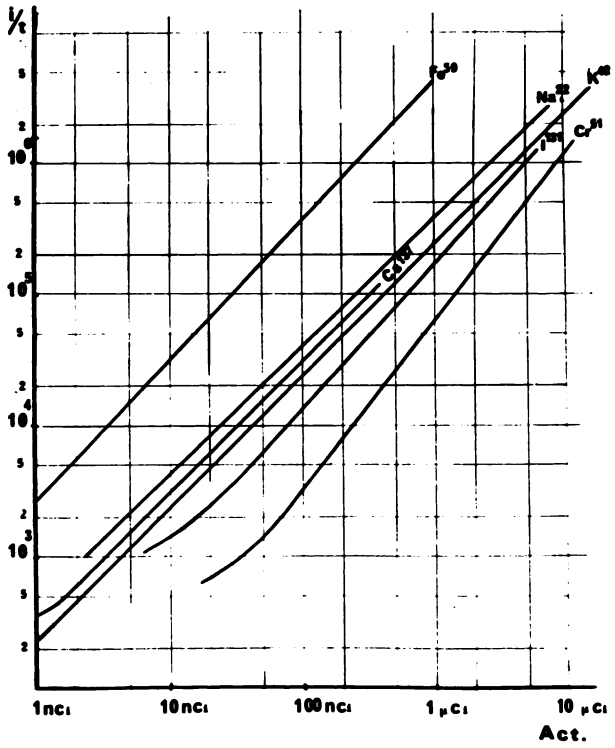

FIG. 7. Linearity of efficiency. Abscissa gives activity of point sources; ordinate gives impulses (counting time: 200 sec) obtained with measurement ranges in Table 3.

A correction factor is only rarely needed, which is very valuable in clinical use, especially for long-range metabolic studies.

CALIBRATION

The combination of low resolution and high efficiency inevitably leads to difficulty in discriminating between two or more gamma-ray energies since each isotope contributes to all channels. Little is gained by reducing counting channel width since the spectra are continuous, and reducing the channel width brings about a reduction in efficiency with no advantage gained. From the data shown in Tables 2 and 3, the data shown in Table 4 have been calculated. Table 4 shows the contribution to each of six counting channels by the isotopes ^{51}Cr, ^{131}I, ^{137}Cs, ^{22}Na, ^{59}Fe and ^{40}K, each of which is in frequent clinical use. Of particular interest is the fact that the mutual interference of ^{137}Cs and ^{40}K is by no means negligible although these isotopes are distinctly separate spectrally.

A biological body always contains ^{137}Cs as well as ^{40}K. It is evident that the separation of these isotopes cannot be brought about on the physical basis of spectrometry (counting of ^{40}K in the high-energy

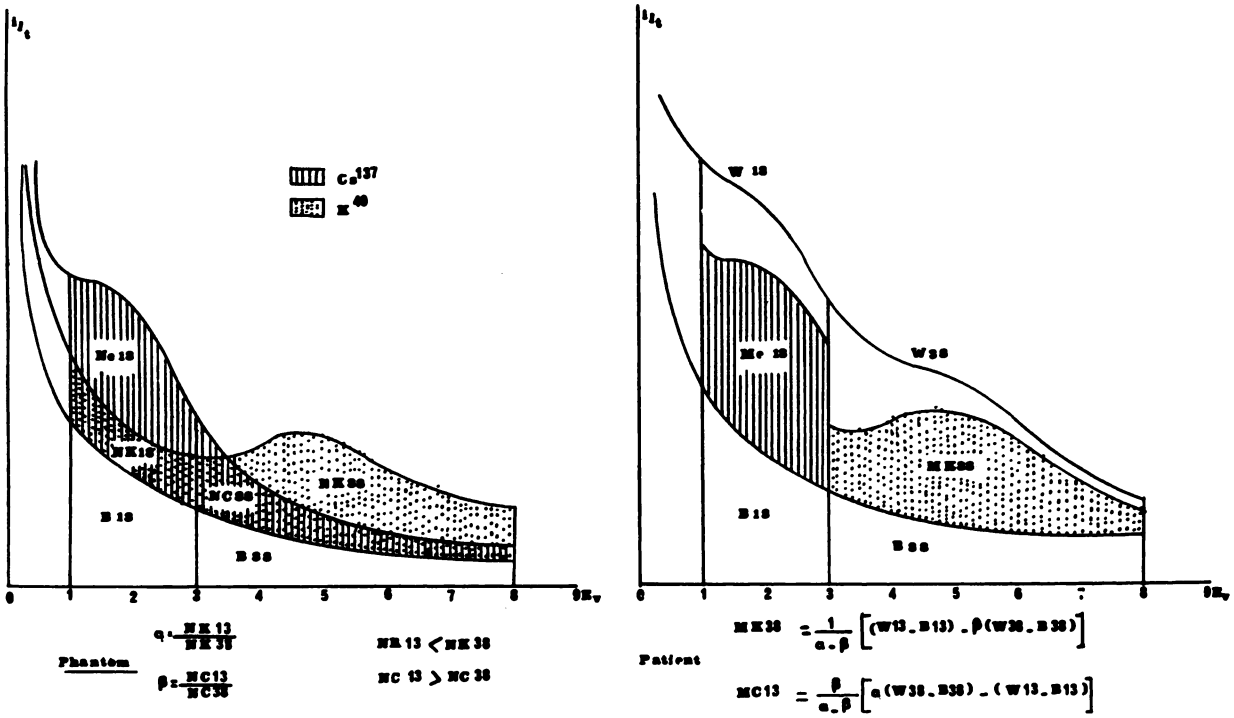

FIG. 8. Calibration procedure for ^{40}K and ^{137}Cs. Left shows measurements in phantom; right shows measurements in patient.

TABLE 4. INTERFERENCES CAUSED BY SEVERAL ISOTOPES*

Isotopes & measurement range (volts)	cpm/μCi in bands by following isotopes					
	^{51}Cr	^{131}I	^{137}Cs	^{22}Na	^{59}Fe	^{40}K
^{51}Cr	76,700	714,760	488,600	385,800	343,600	494,000
0.5–2	100%	932%	637%	503%	448%	644%
^{131}I	78,000	776,500	774,800	553,100	486,100	599,000
0.5–3	10.0%	100%	99.8%	71.2%	62.3%	77.2%
^{137}Cs	31,500	360,100	618,400	401,400	320,100	390,000
1–3	5.1%	58.2%	100%	64.9%	51.8%	63.0%
^{22}Na	31,800	379,500	799,700	704,800	762,700	650,000
1–6	4.5%	53.8%	113%	100%	108%	92.2%
^{59}Fe	3,580	81,200	471,400	537,500	650,400	449,000
2–7	0.5%	12.5%	72.4%	82.6%	100%	69.0%
^{40}K	400	19,400	185,100	414,800	544,800	414,000
3–8	0%	4.7%	44.7%	100%	131%	100%

* Sensitivity in cpm/μCi and percentage of the value given by reference isotope in each band.

TABLE 5. ACCURACY OF POTASSIUM MEASUREMENTS

30 daily measurements (Feb–Mar, 68) of single individual	Measurements of homogeneous student population
Male : 35 yr—healthy	Male : No. 125; 19–22 yr
82 kg	Mean : 2.15 gm/kg
Body potassium : 130 gm	σ : 0.16 gm/kg (7.4%)
1.58 gm/kg	Female : No. 125; 18–21 yr
σ : 6.5 gm 5%	Mean : 1.86 gm/kg
0.08 gm/kg	σ : 0.20 gm/kg (11%)

range where the ^{137}Cs contribution becomes vanishingly small could not produce a high enough efficiency for accurate measurements of body potassium). However, the remarkable stability of the apparatus makes possible the use of calculated correction factors for the contribution of two isotopes in standardized channels (*8*).

In the case of human body counting, the standard comprises a polyethylene phantom filled with 70 liters of sucrose solution. The calibration procedure consists of the successive measurement of 150 gm of potassium and 5 nCi of ^{137}Cs in the phantom and then computing the contribution ratios between the two channels defined in Table 3. Thereafter, patient measurements are carried out using a system of two equations with two unknowns. Figure 8 depicts the method. It has been proved that the coefficients are constant for the usual range of ^{40}K and ^{137}Cs activities.

Under these conditions, the estimation of human body potassium is carried out in 200 sec to an accuracy of 5%. Table 5 shows the results obtained from 30 daily measurements on a single individual and from 250 students in the 18–22-year age group.

CONCLUSIONS

The properties of stability, background reduction, efficiency and resistivity of the Liège whole-body counter make it very suitable for clinical use despite the modest energy resolution. Preliminary studies of body potassium support these findings.

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