KFKI-1979-95

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INTERNATIONAL INTERCOMPARISON OF WHOLE BODY COUNTERS

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CENTRAL
RESEARCH
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PHYSICS

BUDAPEST

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HU ISSN 0368 5330
ISBN 963 371 622 5

ABSTRACT

An international intercomparison of whole-body counters with the participation of 7 laboratories from 5 member countries was organized in 1976 by the Consultative Scientific and Technical Council for Radiation Protection of the CMEA. The Health Physics Department of the Central Research Institute for Physics also, participated in this intercomparison. The main aim of the participation was to check our calibration method, measuring and evaluation procedures to determine their suitability for routine measurements and to investigate the advantages and drawbacks of applying different measuring geometries and evaluation methods. The final results of the intercomparison including our data in more detail are shown in the paper. The results obtained for different measuring geometries, evaluation methods and phantom sizes applying a simple calibration procedure are also given. The results show that a simplified calibration method using point sources embedded in an elliptic cylinder shaped scattering medium and a computerized least square fitting procedure in the evaluation of measurements combine to yield a final accuracy of ±15% in the gamma energy range of 250-1500 keV assuming uniformly distributed sources, a wide range of body sizes, and the choice of a particular measuring geometry.

АННОТАЦИЯ

В соответствии с рабочим планом координационного научно-технического совета по радиационной безопасности /Рабочей группы по радиационной безопасности/ СЭВ в 1976 году было организовано международное сличение спектрометров излучения человека с участием 7-и лабораторий из 5-и стран-участниц СЭВ. При проведении сличения принял участие и Главотдел радиационной безопасности ИЛЭ ЦИФИ с той целью, чтобы, с одной стороны, проверить методы калибровки, измерения и оценки, которые считались пригодными для проведения рутинных измерений, а, с другой стороны, рассмотреть преимущества и недостатки различных геометрических условий измерения и методов оценки. В работе описываются результаты сличения и подробно излагаются результаты наших измерений. Даются также и результаты, полученные в различных геометрических условиях и методов контроля путем простой калибровки для всех фантомов различного размера, подвергнутых измерению. На основе результатов можно установить, что если комбинировать метод калибровки с точечным источником - применяя рассеиватель эллиптически-цилиндрической формы - с приближением по методу наименьших квадратов при разложении спектров на ЭВМ, то в случае равномерного распределения точечных источников могут быть получены результаты с точностью ± 15% в области энергии гамма-излучения 250-1500 кэв и в широком диапазоне размера тела, независимо от выбранной геометрии измерения.

KIVONAT

A KGST Sugárbiztonsági Tudományos-müszaki Koordinációs Tanács munkatervében foglaltaknak megfelelően 1976-ban 5 ország 7 laboratóriumának részvételével egésztestszámlálós összemérést szerveztek. A KFKI Sugárvédelmi Főosztálya is részt vett az összemérésben azzal a céllal, hogy egyrészt letesztel-jük a rutin mérésekre alkalmasnak tartott kalibrációs eljárásunkat, mérési és kiértékelési módszerünket, másrészt megvizsgáljuk különböző mérési geometriák és kiértékelési módszerek előnyeit és hátrányait. A dolgozatban bemutatjuk az összemérés végeredményét, ezen belül részletesen tárgyaljuk a saját mérési eredményeinket. Megadjuk a különböző mérési geometriák, kiértékelési módszerek által szolgáltatott eredményeket, melyeket egy egyszerü kalibrációs eljárással az összemérésben szereplő különböző méretü fantomokra nyertünk. Az eredményekből megállapitható, hogy egy elliptikus henger alaku szóróközeget alkalmazó pontforrásos kalibrálás párositva egy legkisebb négyzetes illesztés elvén alapuló számitógépes spektrumdekomponáló eljárással, egyenletes forráseloszlás esetén megfelelő, mintegy ±15%-ra pontos eredményt tud szolgáltatni a 250-1500 keV gamma energia és széles testméret tartományban, függetlenül a mérési geometria megválasztásától.

1. INTRODUCTION

The CMEA Consultative Scientific and Technical Council for Radiation Protection organised in 1976 an intercomparison of measurements performed in whole body counter laboratories of the member countries. The aim was, in addition to offering a possibility for comparing the results of different laboratories, to check on the methods used for measurement and evaluation in these laboratories. The intercomparison measurements were restricted to the most frequently occurring case in the practice of radiation protection, namely, to that of homogeneous activity distribution within the human body in the range of gamma radiation energies from 200 to 2000 keV. The organizational work was undertaken by the Radiation Protection Department of the Institute of Nuclear Research /Swierk, Poland/. The participants agreed beforehand on the types and the approximate amounts of activity to be measured as well as on the types of phantom to be used. It was also decided that in order to exclude errors in activity standardization, point sources of the same origin would be made available of the radionuclides in question. According to the agreement the organizing institute prepared five BOMAB type phantoms of bodies different in shape.

The phantoms were then filled with the aqueous solution of a mixture containing known values of the activities of the following isotopes: ^{203}Hg /279 keV/, ^{54}Mn /840 keV/, ^{65}Zn /1114 keV/ and ^{40}K /1460 keV/. The total activity of the mixture ranged from 100 to 500 nanocuries in a distribution not known by the participants, viz. 7 laboratories from Czechoslovakia, the German Democratic Republic, Hungary, Poland, Romania and the Soviet Union [1]. Hungary was represented by the Health Physics Department of the Central Research Institute for Physics /KFKI/.

The primary aim of our perticipation was to utilize the possibility offered by the intercomparison to test the extensive applicability of the methods of measurement, calibration and evaluation chosen locally as the most expendient, and to obtain information on the likely limitations of these methods. At the same time we wished to compare the usefulness of the various geometries, calibration and evaluation methods used in our laboratory for measuring different gamma energies and for bodies of different shapes. With the primary aim outlined above in mind, the results submitted for the intercomparison were those obtained with methods most generally applicable to routine jobs and not with a procedure which would be the most suitable for the given task.

2. METHOD OF MEASUREMENT

2.1 Site

The measurements were performed on the whole body counter built in 1964 in the Central Research Institute for Physics [2]. The scintillation spectrometer consists of a 6"x4" /approx. 15x10 cm/ low background NaI/Tl/ crystal mounted on a photomultiplier coupled to a multichannel analyser. The signals processed by the analyser are recorded on punch tape for evaluation by computer. The constant energy calibration was ensured by a peak stabilization system. The measuring room is flushed by filtered air /*Fig. 1*/.

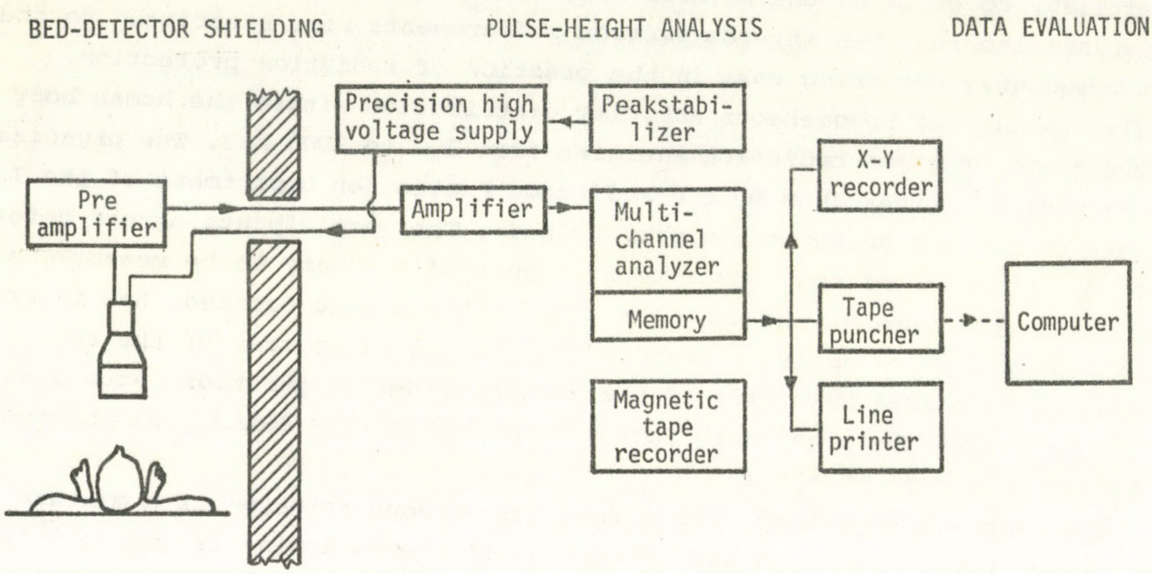


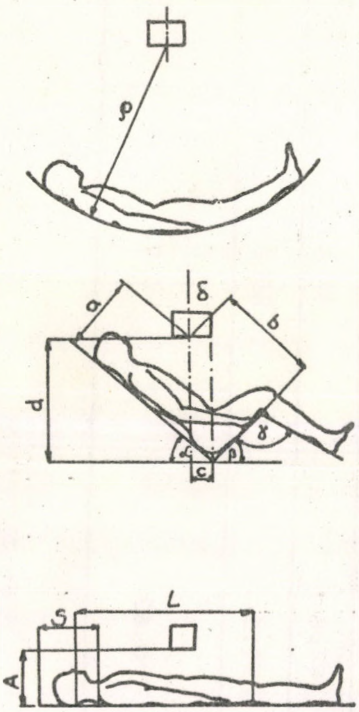
Fig. 1

Arrangement of measurement with whole-body counter

2.2 Geometry

The calibration of the scintillation spectrometer was carried out for arc /A/, chair /B/, scanning /C1/ and "scanning-end-stop" /C2/ geometry /*Fig. 2*/.

In the calibration a BOMAB phantom of normal size was used for ^{40}K, while a simpler calibration procedure was applied for ^{203}Hg, ^{54}Mn and ^{65}Zn. In the latter case the referene spectra to be expected for a BOMAB phantom of normal size were produced with a point source placed into a body-equivalent scattering medium having the form of an elliptical cylinder /Presdwood phantom/. The difference between the counting efficiencies in the whole range of energies was taken into account by a single conversion factor determined at 662 keV [3].

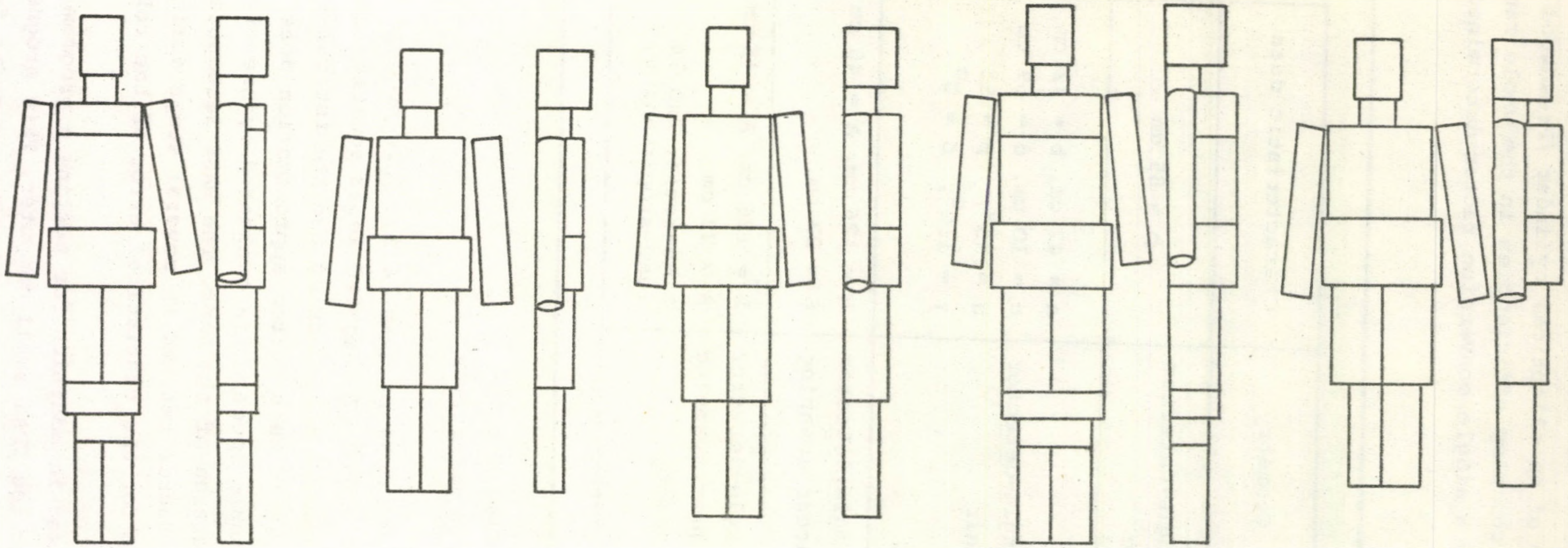


Code number	Geometry	Characteristic data
A	single-detector arc	ρ = 85 cm
B	single-detector chair	a = 42 cm, b = 42 cm, c = 10 cm, d = 59 cm, α = 35°, β = 55°, γ = 110°, δ = 0°
C1	single-detector linear scanning	L = 126 cm, A = 45 cm, S = 23 cm
C2	single-detector linear scanning end-stop	L = 126 cm, A = 45 cm, S = 23 cm, time-ratio: 2x0.14 (end-stop/running)

Fig. 2
Measuring geometries

The spectra were evaluated by our DAS4 program [4,5]. This program decomposes the sample spectrum by the method of weighted least squares taking the background to be a separate component and ignoring the statistical error of the standard reference spectra. Where this latter approximation does not hold /e.g. in arc geometry/, the sample spectrum is evaluated by use of the DAS8 program, which is a refined version of the DAS4. The DAS8 decomposes the spectrum by use of a weighting factor refined in several steps during an iteration procedure accounting also for the statistical error of the reference spectra.

The intercomparison was utilized in addition for testing a program named STRIP written in FOKAL language for the TPAi small computer. This program works by the stripping method. It divides the range of gamma energies from



Tall thin	Small thin	Standard	Tall thick	Small thick

	Tall thin	Small thin	Standard	Tall thick	Small thick
h[cm]	184	152	170	187	155
Q[kg]	59.5	50.6	67.8	99.1	83.1
V[dm^3]	50.4	43.6	59.5	85.9	75.3
$\sqrt{\frac{Q}{h}}$ $\left[kg^{\frac{1}{2}}\ cm^{-\frac{1}{2}}\right]$	0.57	0.58	0.63	0.73	0.73

Fig. 3

Most important data of phantoms used for the intercomparison

0.1 to 2.0 MeV into seven intervals; it then establishes a statistical significance according to which it evaluates the activities from the characteristic energy peaks of the selected intervals. The results can be read from the data output in protocol format [6].

3. RESULTS

The data of phantoms used for the intercomparison are given in *Fig. 3*. The phantoms consisted of elliptical polyethylene cylinders; they were filled with the aqueous solution of the isotopic mixture of calibrated activities.

3.1 Intercomparison

For the intercomparison, results obtained from measurements in scanning-end-stop geometry were submitted. With all five phantoms 2-3 parallel measurements were performed. The spectra were evaluated by computer using the DAS4 program. The calibrating measurements were carried out /except for ^{40}K/ with the standard point sources sent by the organizers and placed in the centre of the Presdwood phantom. In the evaluation corrections for body shape and size were not applied. The results of the measurements are given in detail in *Table 1*.

Table 1

Measured values with errors for scanning-end-stop geometry

	^{203}Hg			^{54}Mn			^{65}Zn			^{40}K		
	A_j	σ_j	σ	A_j	σ_j	σ	A_j	σ_j	σ	A_j	σ_j	σ
	[nCi]			[nCi]			[nCi]			[g]		
Small thin	174.8 173.0	3.5 3.5	11	93.0 91.3	2.7 2.7	5	224.6 224.0	5.1 5.0	14	129.4 107.3	13.1 12.3	5
Tall thin	192.1 192.4	3.9 4.3	12	106.4 103.7	3.0 3.1	6	246.9 250.1	5.6 6.1	16	116.9 130.6	13.7 15.2	5
Standard	234.5 232.6 233.0	3.9 4.0 3.9	12	135.3 126.9 126.5	3.0 3.1 3.0	6	295.9 307.5 299.2	5.6 6.0 5.7	15	168.4 162.4 153.0	13.6 14.3 13.7	-
Small thick	284.8 284.2	4.0 4.4	18	149.6 150.3	3.0 3.2	9	358.4 353.1	5.8 6.4	23	200.1 170.0	13.8 14.3	7
Tall thick	317.5 315.8	4.4 4.7	20	172.6 174.4	3.3 3.6	11	396.8 408.8	6.5 6.8	26	199.5 186.8	15.0 15.0	8

The errors of the final results sent in for intercomparison are calculated for the arithmetic mean of parallel measurements. The errors of the mean values were calculated from the statistical errors arising from the computer decomposition of parallel measurements by least square fit.*

The systematic error arising from the method, that is the error of the conversion factor of a point source to a volume source, contains the error of the factor determination at a given energy and of that of the estimation of the dependences on energy and on body shape [3]. All these systematic errors amounted to 4-7% depending on the size of the phantom and on the gamma energy and were simply added to the statistical errors. The uncertainties in the activity of sources used for calibration were neglected since activities measured on point sources and phantoms were supposed to contain the same standardization error of measurement. The errors arising from the correction for decay were also thought to be negligible.

Table 2

Expected values of activities in phantoms at the time of reference [1]

Type of phantom	^{203}Hg [nCi]	^{54}Mn [nCi]	^{65}Zn [nCi]	^{40}K [g]
Small thin	162.1±4.5	93.7±2.4	213.9±3.9	114.3
Tall thin	187.5±5.3	108.4±2.8	247.4±4.5	132.2
Standard	221.4±6.2	128.0±3.3	292.2±5.3	156.1
Small thick	272.5±7.6	157.5±4.1	359.7±6.5	192.1
Tall thick	319.4±8.9	184.6±4.8	421.6±7.6	225.1

In *Table 2*, the expected activity values of the isotopes contained are listed for each of the phantoms at the time of reference. The results sent in by the various laboratories are summarized in *Table 3*.

The tabulated data are represented graphically in *Figs 4* and *5*. Results of the KFKI whole-body counter laboratory are listed under code number 4.

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*If the activity values for the i'th isotope computed by the DAS4 program from n parallel measurements are given successively as $A_{i1}, A_{i2}, \ldots A_{in}$ with the standard deviations $\sigma_{i1}, \sigma_{i2}, \ldots \sigma_{in}$, respectively, then the mean value is $\frac{1}{n} \sum_{j=1}^{n} A_{ij}$ with the error $\frac{1}{n} \left(\sum_{j=1}^{n} \sigma_{ij}^2 \right)^{\frac{1}{2}}$ [7].

Table 3

Summarized results of laboratories taking part in the intercomparison of whole-body counter measurements [1]

Lab. code num.	Type of phantoms	^{203}Hg A [nCi]	^{203}Hg ΔA [%]	^{54}Mn A [nCi]	^{54}Mn ΔA [%]	^{65}Zn A [nCi]	^{65}Zn ΔA [%]	^{40}K A [g]	^{40}K ΔA [%]
	small thin	159±16	-2	83±8	-11	195±20	-9	126±13	+10
	tall thin	178±18	-5	90±9	-17	207±21	-16	136±14	+3
No.1	standard	227±23	+3	113±11	-12	261±26	-11	161±16	+3
	small thick	298±30	+6	152±15	-3	351±35	-2	213±21	+11
	tall thick	329±33	+3	163±16	-12	378±38	-10	244±24	+8
	small thin	152±12	-6	61.4±4.4	-34	196±15	-8	122±19	+7
	tall thin	177±13	-6	70.0±4.8	-35	228±17	-8	131±21	-1
No.2	standard	204±15	-8	87.2±5.9	-32	265±20	-9	152±21	-3
	small thick	239±18	-12	100.2±6.7	-36	333±25	-7	173±22	-10
	tall thick	282±21	-14	119.1±7.3	-35	387±28	-8	203±31	-10
	small thin	168±15	+4	79±6	-16	202±15	-6	128±8	+12
	tall thin	185±17	-1	91±7	-16	224±17	-9	145±11	+10
No.3	standard	228±21	+3	110±9	-14	276±20	-6	172±11	+10
	small thick	298±28	+6	145±12	-8	362±27	+1	226±14	+18
	tall thick	331±30	+4	164±14	-11	407±30	-3	254±17	+13
	small thin	174±14	+7	92±8	-2	224±18	+5	118±14	+3
	tall thin	192±15	+2	105±9	-3	249±20	+1	124±15	-6
No.4	standard	233±14	+5	130±8	+2	301±18	+3	161±8	+3
	small thick	284±21	+4	150±11	-5	356±27	-1	185±18	-4
	tall thick	317±24	-1	174±13	-6	403±30	-4	193±19	-14
	small thin	123.4±13.7	-24	91.7±7.4	-2	213.1±13.6	0	155.8±15.5	+36
	tall thin	152.7±15	-19	103.2±8.3	-5	241.1±12.5	-3	170.0±21.4	+29
No.5	standard	161.8±16	-27	123.1±7.3	-4	291.6±18.3	0	191.1±13.9	+22
	small thick	184.3±20.1	-32	150.0±10.9	-5	357.4±20.6	-1	252.9±24.8	+32
	tall thick	210.8±19.2	-34	166.7±13.7	-10	388.5±25.3	-8	279.4±29.6	+24
	small thin	119±12	-27	92±9	-2	220±22	+3	120±12	+5
	tall thin	134±13	-29	104±10	-4	251±25	+1	131±13	-1
No.6	standard	153±15	-31	125±13	-2	294±29	+1	163±16	+4
	small thick	224±22	-18	164±16	+4	376±38	+5	198±20	+3
	tall thick	231±23	-28	181±18	-2	418±42	-1	227±23	+1
	small thin	139±9	-14	81±4	-14	200±10	-6	132±8	+15
	tall thin	164±11	-13	90±5	-17	228±11	-8	144±8	+9
No.7	standard	191±11	-14	106±6	-17	266±14	-9	165±9	+6
	small thick	228±16	-16	123±7	-22	308±15	-14	192±10	0
	tall thick	266±17	-17	135±9	-27	334±17	-21	202±11	-10

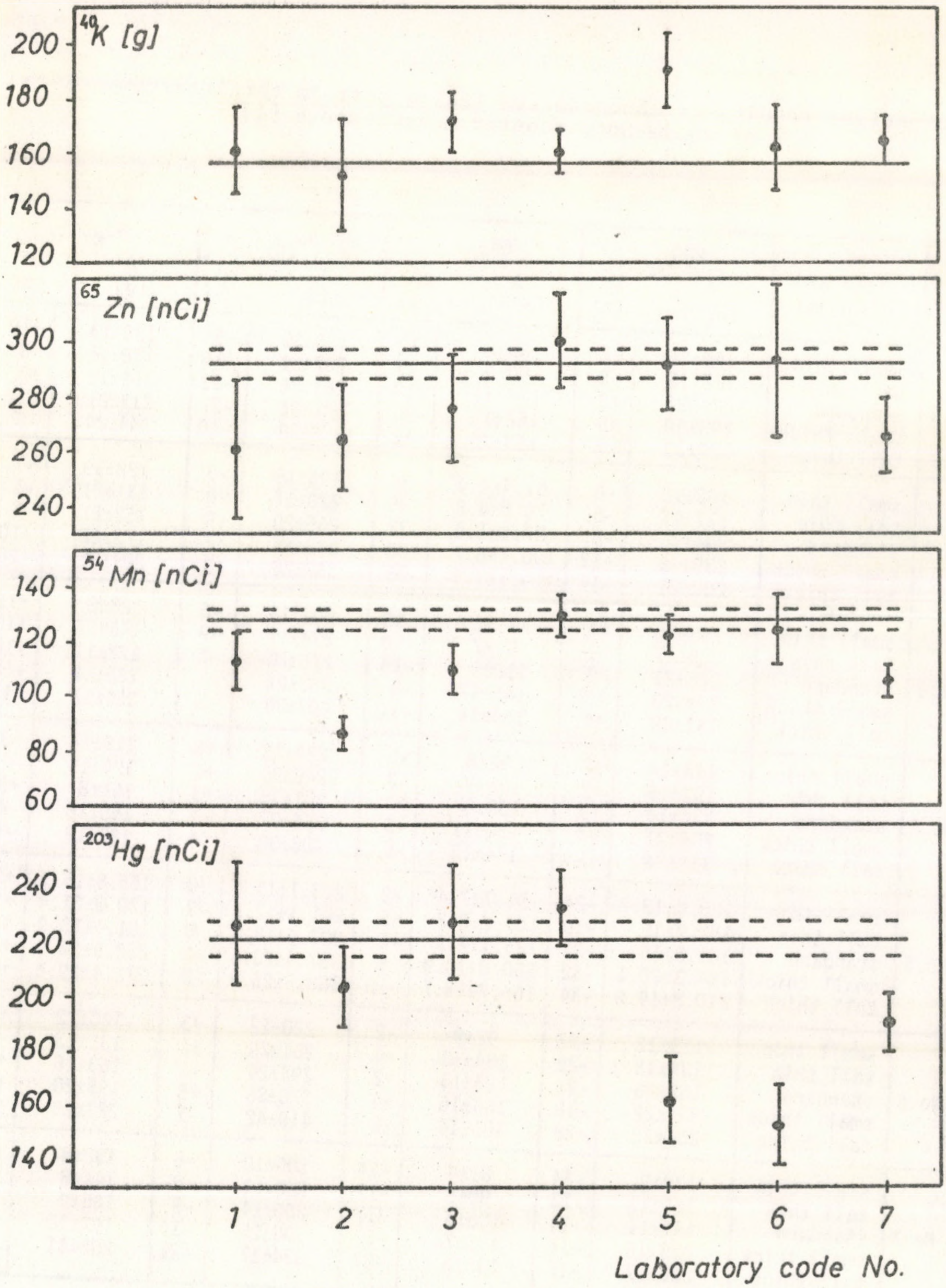

Fig. 4

Results of measurement on standard phantom submitted by laboratories taking part in the intercomparison. The expected values and errors are indicated in the figure. Our own /KFKI/ results are represented by code number 4. [1]

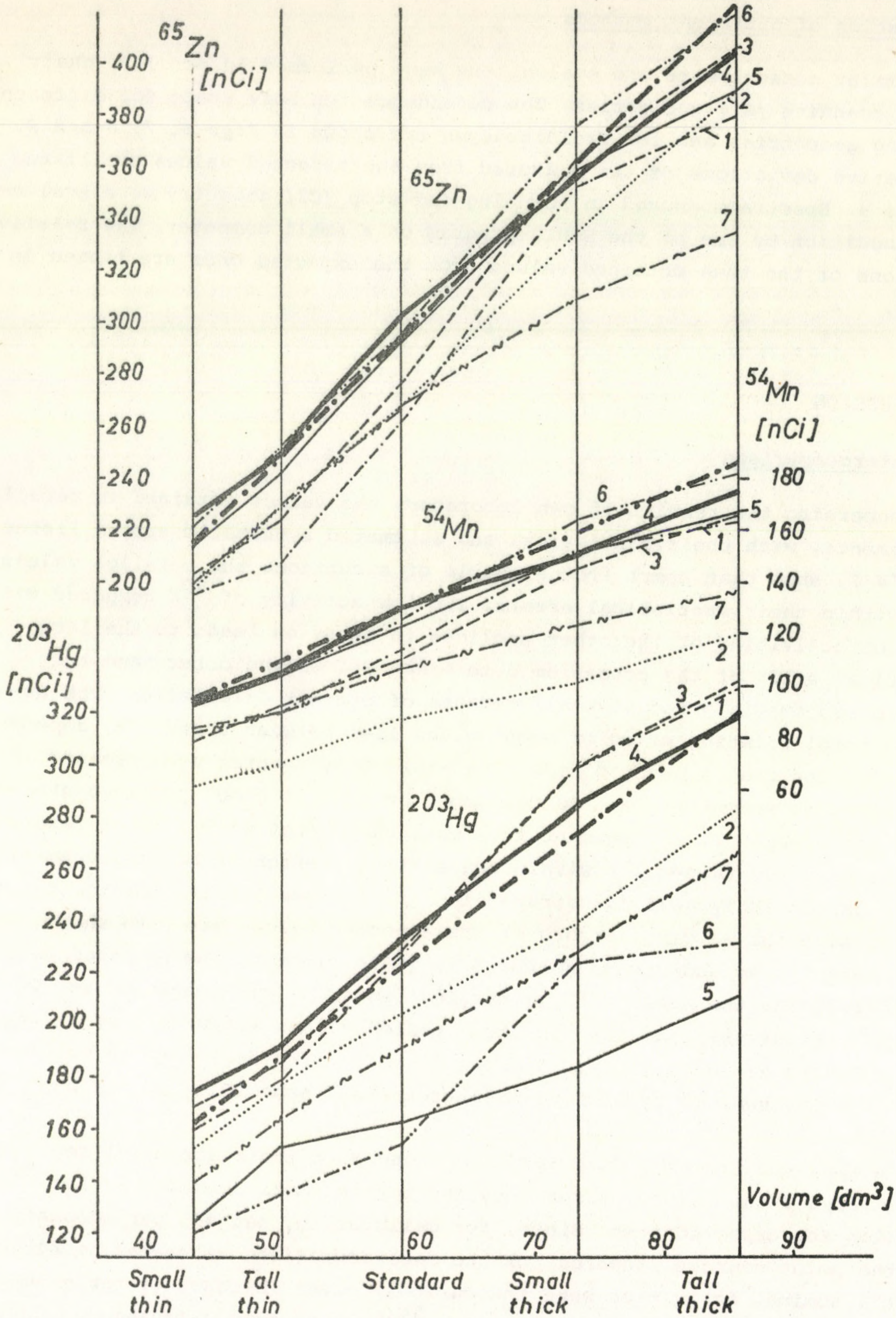

Fig. 5

Results submitted for ^{203}Hg, ^{54}Mn and ^{65}Zn. The expected activity values are indicated by a dot-dash line. KFKI's results are represented by code number 4. [1]

3.2 Testing of different methods

Similar measurements and evaluations were performed in arc /A/, chair /B/ and scanning /C1/ geometries. The dependences on body shape for different measuring geometries and for radioisotopes are shown in *Figs 6, 7, 8* and *9.* The relative deviations of the measured from the expected values are listed in *Table 4.* Spectra measured in scanning-end-stop /C2/ geometry were evaluated in addition by use of the STRIP program on a small computer. The relative deviations of the thus obtained values from the expected ones are listed in *Table 5.*

4. DISCUSSION

4.1 Intercomparison

Concerning the results of own laboratory the values obtained in parallel measurements, with their statistical and estimated systematic errors listed in *Table 1*, show that apart from a couple of exceptions the parallel values agree within their statistical errors. The low activity of ^{40}K compared with values of activities of the other nuclides in question leads to the large statistical error of the potassium determination. On the other hand the expected systematic error is small because of correct calibration. The estimated total relative error of mean values lies between 5 and 12%, depending on the isotope and on phantom size. For whole-body counter measurements this uncertainty is acceptable and is confirmed by data of other participants as listed in *Table 3.* It is apparent from this table that with a single exception the expected values lie within the estimated error of our measurements. This is particularly well illustrated in *Fig. 4* where for the phantom of standard size the marginal errors of the expected values are also shown. Each of our data listed under code number 4 is quite close to the expected value even considering the not too large marginal error of our measurements. The agreement is satisfactory for the three radionuclides measured also on the other phantoms as shown in *Fig. 5.* Considerable differences are to be seen in the results sent in by different laboratories, especially in the case of ^{203}Hg.

As apparent from the data in *Table 3* and from their graphical representation in *Fig. 5* the values measured by the participants, especially for ^{54}Mn, are below the expected ones. Since, for calibration, not all participants used the point sources prepared for the intercomparison it seemed possible that the nominal activities were inaccurately given /because of for example, in standardization/. For this reason the ^{54}Mn point source having an uncertainty of ± 4.2% sent by the organizers was compared later with the standard point source of uncertainty ± 1.5% prepared by the Hungarian National Office of Measure /NOM/. It was found that the nominal value specified by the organizers exceeded by 5% that of the NOM standard. This should not influence our values measured on the phantoms and sent for intercomparison assumming the ^{54}Mn activity in the phantom to have the same error.

The slight understimate obtained for the tall, thick phantom is probably due to the simplified calibration procedure. This error is particularly significant in the potassium determination.

4.2 Testing of different methods

Inferences which can be drawn from the data in *Table 4* and from the curves in *Figs 6, 7, 8* and *9* can be summarized as follows:

Table 4

Relative deviations of measured from expected values of activaties for different measuring geometries

Geometry		Relative deviation [%]			
		^{203}Hg	^{54}Mn	^{65}Zn	^{40}K
Small thin	C2	6.5	-6.2	2.0	3.6
	C1	11.8	-0.9	-0.4	5.5
	B	12.2	1.1	8.7	3.6
	A	2.2	-6.4	3.2	2.6
Tall thin	C2	2.0	-7.6	-2.3	-6.4
	C1	9.7	-9.1	-5.3	-14.1
	B	6.3	-8.1	0.7	-0.2
Standard	C2	5.0	-3.4	0.2	3.3
	C1	7.4	-4.5	-6.3	-9.7
	B	13.1	-0.2	6.6	1.3
	A	4.8	-4.1	0.0	3.7
Small thick	C2	3.9	-9.1	-3.8	-3.7
	C1	7.5	-3.3	-4.0	-5.3
	B	10.5	-1.5	2.9	2.5
Tall thick	C2	-1.4	-10.3	-7.0	-14.2
	C1	3.6	-9.4	-9.7	-11.2
	B	10.6	-4.1	1.9	1.6
	A	6.2	-5.5	-1.6	-16.0

Results obtained in different geometries agree within $\leqq$ 16% with the expected values, while the average absolute deviation is merely 5.5%. This includes an average of 3.7% for ^{65}Zn and even for ^{203}Hg, the calibration and evaluation of which entail the largest error, the deviation is not more than 6.9%. The best agreement was obtained for ^{65}Zn where the results lie around the expected values. The deviation pattern is similar for ^{40}K but the deviations are larger than for ^{65}Zn. In the case of ^{54}Mn the sign of the deviations is practically always negative with an average of 5.1% while the 6.8% average deviation for ^{203}Hg is mainly in the positive direction. The deviation in the

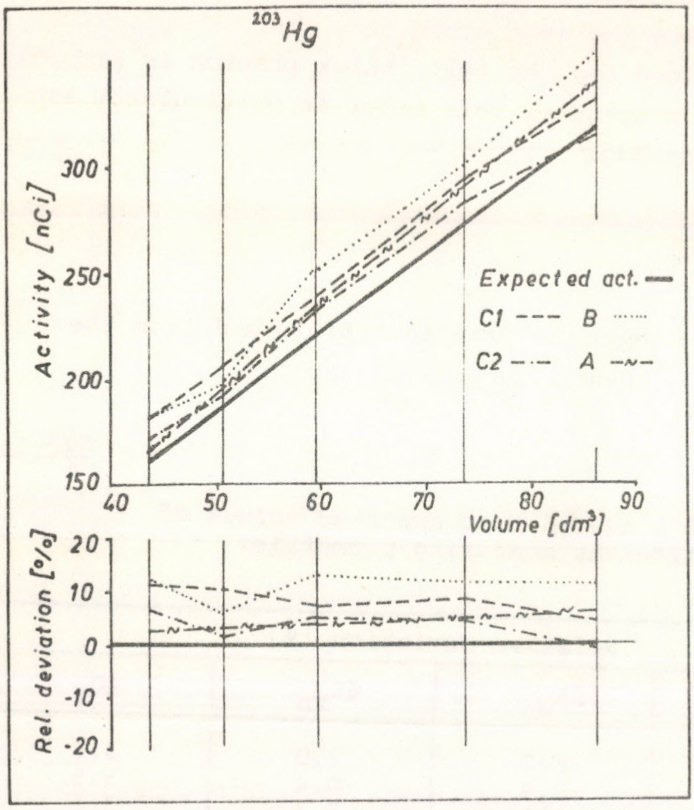

Fig. 6

KFKI's results for ^{203}Hg as a function of phantom shape in different geometries

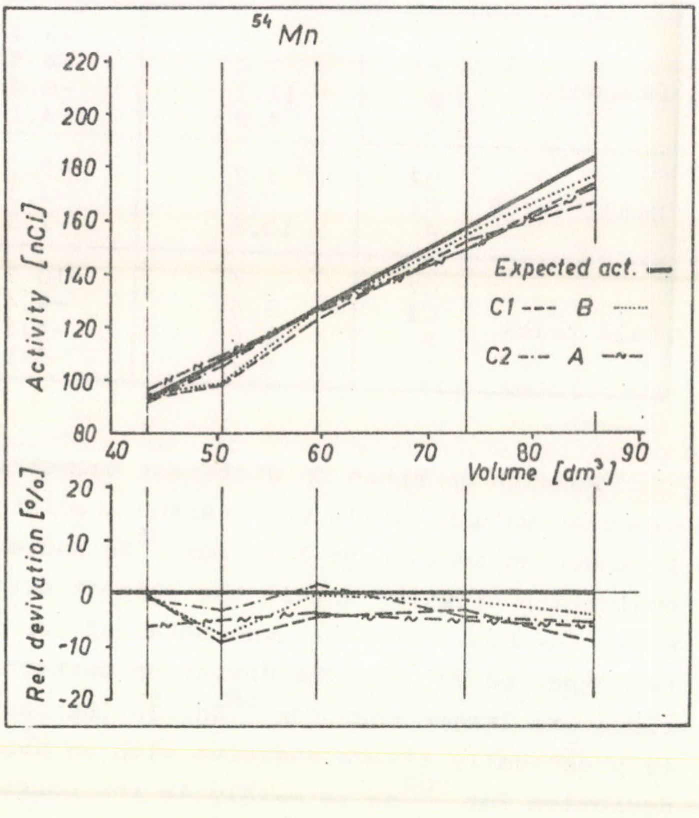

Fig. 7

KFKI's results for ^{54}Mn as a function of phantom shape in different geometries

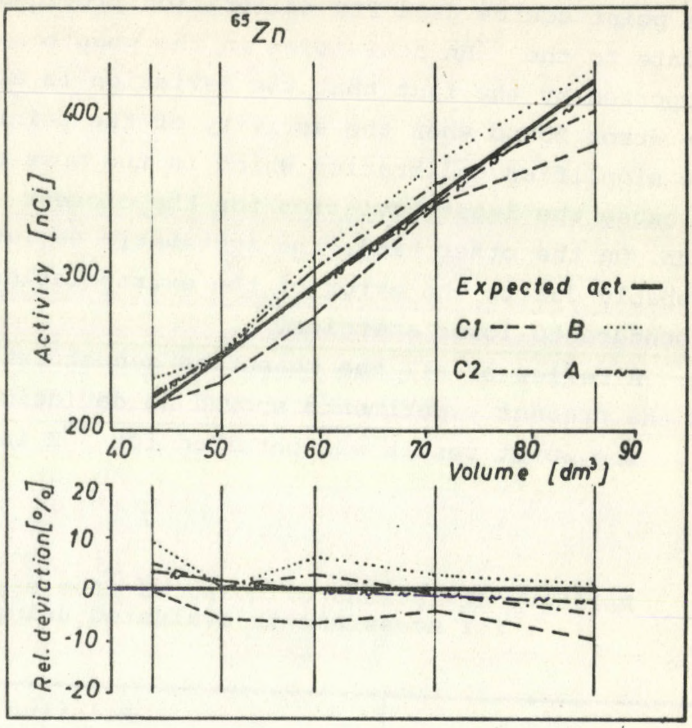

Fig. 8

KFKI's results for ^{65}Zn as a function of phantom shape in different geometries

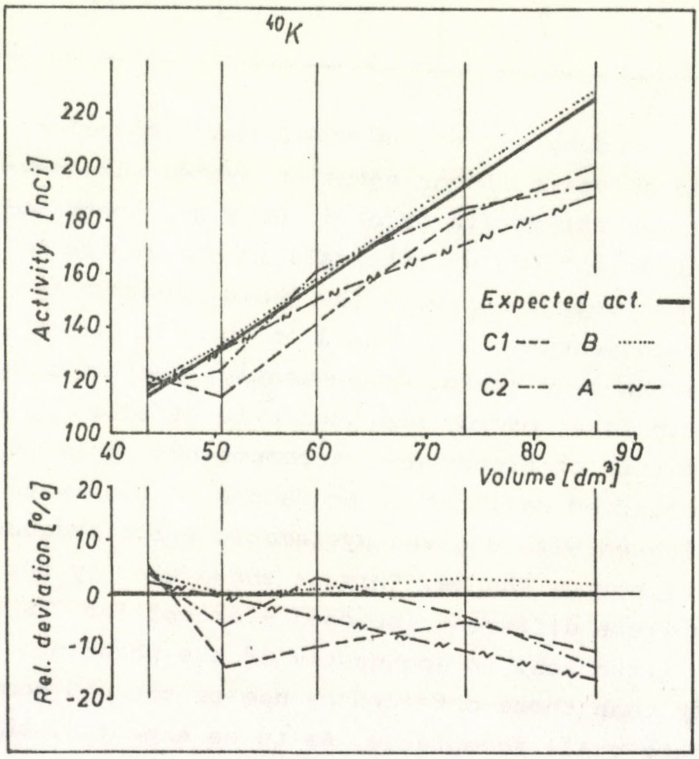

Fig. 9

KFKI's results for ^{40}K as a function of phantom shape in different geometries former case could be caused by the possible error of the nominal activity of the point source used for calibration provided that this error does not relate to the ^{54}Mn activities in the phantoms, as mentioned earlier. This is supported by the fact that the deviation is almost of the same magnitude as the error found when the activity of the point source was checked and that the simplified calibration which is the most accurate for 662 keV is expected to cause the least deviation for the closest lying 840 keV radiation from ^{54}Mn. On the other hand, the systematic deviation observed for ^{203}Hg is probably due to the error of the extrapolation of this simple calibration procedure to lower energies.

A review of all the measuring geometries, phantoms and isotopes involved in the present experiments showed no deviation exceeding +13 or -16%. The worst result was obtained for ^{40}K in the tall and thick phantom.

Table 5

Relative deviations of measured from expected values of activities for measurements evaluated using the STRIP program

Geometry: C2	Relative deviation [%]			
	^{203}Hg	^{54}Mn	^{65}Zn	^{40}K
Small thin	-14	-2	11	-16
Tall thin	-16	-1	11	8
Standard	-5	-1	9	0
Small thick	-11	-8	6	23
Tall thick	-17	-7	3	-9

The data in *Table 5* were obtained by use of the STRIP small computer program. Essentially this program solves a linear equation system with several unknowns by applying the triangular matrix of efficiency and contribution coefficients obtained for different energy intervals in the course of calibration. This procedure successively decomposes the gamma spectrum by starting with the highest energy component. It is based on the determination of the total number of counts in the peak areas. Consequently, the accuracy of the determination of relatively lower energy components is affected by the systematic error in the determination of higher energy components. This is particularly critical if the simplified calibration procedure is used when the coefficients have to be evaluated with a given systematic error because of the not completely identical spectrum shapes. This is shown also by the data for C2 geometry in *Table 5* where different isotopes - except for ^{40}K - exhibit devitations in the same direction, independently of the phantom shape. The deviations are larger than those obtained by use of the DAS computer programs but the results are still acceptable. As to be expected, the best results were obtained for the standard phantom.

5. CONCLUSION

Calibration with a point source placed in an elliptical cylinder shaped scattering medium permits uniformly distributed activities to be determined to a reasonable accuracy /<±15%/ for gamma energies from 250 to 1500 keV in a wide range of body sizes irrespective of the measuring geometry. Results in this range of accuracies can be obtained only with DAS-type computer programs decomposing the spectra by the least squares fit, by which the systematic errors of the calibration are levelled out.

If the activities are uniformly distributed no significant difference is seen in the results obtained with measurements in the four types of geometry under investigation. Thus, the measuring geometry can be chosen by considering such factors as, for example, the value of the activity, convenience, technical conditions, etc. However, if the activity distribution is unknown it is expedient to use scanning-end-stop geometry.

6. ACKNOWLEDGEMENTS

Thanks are due to Mrs. J. Burghardt for help in the measurements and evaluation and to Mr. R. Strommer for writing the small computer program and for evaluating the spectra.

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Kiadja a Központi Fizikai Kutató Intézet
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Készült a KFKI sokszorosító üzemében
Budapest, 1980. január hó

MTA KFKI