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CONTENTS

SAMEVATTING

Terwyl *in-vivo* metings van uraan in die menslike borskas gewoonlik in laeagtergrondtelkamers gedoen is, word 'n metode beskryf waar sodanige metings onder betreklik hoë agtergrondomstandighede uitgevoer kan word. Hiervoor was dit nodig om 'n nuwe ontledingsmetode te gebruik. Daar is gevind dat 'n lineêre verband vir elke individu verkry word wanneer die logaritme van die gammatelkoed teen gamma-energie gestip word. Hierdie verband is geldig vir die energiegebied tussen 90 keV en 300 keV. Die verandering in teltempo's by 90 en 186 keV is dan 'n weergawe van die hoeveelheid aanwesige uraan. Om dit te herlei, word die afwykings vanaf die reguitlyn gekalibreer. Gevoeligheide is sodanig dat minder as ½ MTLL waargeneem kan word.

ABSTRACT

The use of a low-background counting room was considered essential for *in vivo* gamma counting of uranium in the human chest. When such measurements were, however, carried out under relatively high background conditions, this necessitated a new method of analysis. It was found that a linear relationship between LnN and E exists for each individual where N is the count rate per keV and E the energy in keV, for gamma energies between 90 keV and 300 keV. The displacements from this straight line at the energy values of 90 and 186 keV then represent the contribution of the uranium present. These displacements were calibrated for natural uranium. It was possible to detect contamination levels of lower than ½ MPLB.

1. INTRODUCTION

1.1 *In Vivo* Measurement

Monitoring of personnel involved in processes dealing with radioactive or otherwise hazardous materials is generally considered to be of the utmost importance. In the uranium-processing industry urinanalysis has been the principal technique for determining the body burden of uranium in exposed personnel. Several facilities for *in vivo* counting of uranium in the body have been developed lately [1, 2, 3, 4]. Such direct methods of counting are important in cases of the intake of insoluble radioactive materials, such as certain compounds of uranium like the oxides (UO_2, UO_3 and U_3O_8) and tetrafluoride (UF_4) and ammonium diuranate. These insoluble compounds have a long biological half-life (up to 800 days) and do not only contribute to the radiological hazard over a longer period, but cannot be readily detected by excretion analysis. The basic technique for *in vivo* counting of uranium has been reported by Cofield [1] who used a sodium iodide crystal to detect the 186 keV gamma associated with ^{235}U and the peaks around 90 keV associated with ^{231}Th and ^{234}Th, the daughter products of ^{235}U and ^{238}U respectively. Scott and West [2] improved on the sensitivity by using two sodium iodide crystals, one crystal against the patient's back and the other on the chest. Boden *et al* [3] improved the technique even further by using a "phoswich" crystal consisting of a NaI-CsI sandwich crystal to measure transuranium nuclides. The application of this type of phoswich detecter has been well established lately in several laboratories [3, 5, 6].

In all cases low-background counting chambers were used. For the so-called "iron rooms" the walls, ceiling, floor and doors consist of steel panels in a laminated structure. The wall thickness varies between 150 mm and 200 mm for different chambers. Scott *et al* [4] constructed such a chamber as part of a mobile laboratory, weighing approximately 37 t.

The detection levels are normally expressed as a fraction of the Maximum Permissible Lung Burden (MPLB). The most recent ICRP recommendation [7] does not specify organ burdens any longer but suggests an Annual Limit on Intake (ALI) for each particular nuclide. In this publication the MPLB will, however, still be used in order to compare the results with other experimental results. For natural uranium the MPLB is equivalent to 25,6 mg U [1]. Several laboratories obtained limits of detection of lower than 50 % of a MPLB [2, 3, 4], and limits as low as 1/8 MPLB have been achieved [6].

In order to estimate the uranium burden of an exposed person, a relationship of count rates obtained for unexposed individuals is used. The technique involves the gamma counting of unexposed individuals and empirically deriving a statistical equation for predicting the number of counts expected in the energy regions of γ-rays emitted by U and its short-lived daughters. In order to determine the contribution due to Compton scattering, the numbers of counts in adjacent energy regions have to be measured as well. Some parameters relating to the physical properties of the subject, such as mass and length, are also incorporated. Scott and West [2] reported that such a relationship becomes invalid with the passage of time due to changing levels of natural activity in the subjects. They suggested an updating of the equation by monitoring a control population on a continuing basis.

1.2 Gamma Activities from Uranium

The uranium isotopes which are of importance are ^{238}U, ^{235}U and ^{234}U, and their relative abundances in natural uranium are 99,274 %, 0,720 % and 0,0055 % respectively. The actual radiation hazard from inhalation or ingestion of uranium is due to the exposure of tissue to the alpha particles emitted by each of the U isotopes. The *in vivo* measurement depends, however, upon the gamma emission accompanying the alpha decay, since the alpha particles are totally absorbed by surrounding tissue. Although the abundance of ^{234}U in natural uranium is only 0,0055 % its contribution to total alpha activity is 49 %, due to its higher specific alpha activity. When the composition of uranium is selectively changed to obtain an enrichment in ^{235}U, the

^{234}U component also increases. The contribution to the total alpha activity of the ^{234}U component in a compound of 20 % ^{235}U enrichment is 91,5 %. It is therefore clear that the role of ^{234}U is of the utmost importance as far as the radiation hazard is concerned. Unfortunately the ^{234}U component has almost no contribution to the gamma spectrum (only a small peak at 51 keV), and consequently cannot be detected by *in vivo* measurement. The only prominent features of the uranium gamma spectrum are peaks at 186 keV and about 90 keV from ^{235}U, and ^{231}Th plus ^{234}Th, respectively.

The relative magnitudes of the peaks at 186 and 90 keV can serve as an approximate indicator of the isotopic concentration levels. Uranium-235 also has a few small peaks at 110, 143, 163 and 204 keV, but these peaks are too small to be used for identification purposes.

The gamma spectra in air of the MPLB amounts of U at three levels of enrichment, are reproduced in Fig. 1 [1]. The natural uranium exhibits well-defined peaks at 186 and 90 keV. When the uranium-235 component increases as in the enriched compound, the peak at 186 keV becomes more prominent, while the 90 keV peak decreases. The opposite occurs for the depleted compound.

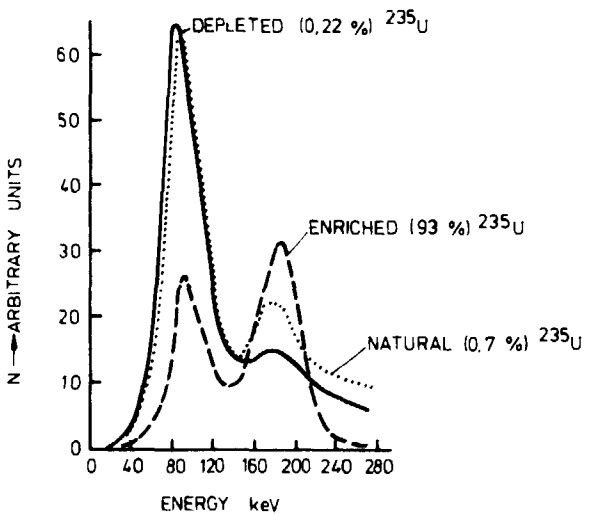

Fig. 1.
Gamma spectra of MPLB amount of uranium (Cofield 1960)

2. BACKGROUND

In the case of a very low background from the surroundings, it is possible to identify peaks in the gamma spectrum originating from a human body. These peaks can be due to natural radioactivity in the body, e.g. ^{40}K, or to foreign material present as a result of contamination. The quantification of these peaks in terms of the amount of radioactive material present is dependent on factors such as the gamma energies of the nuclides and absorption and scattering by the human body. Unless the gamma spectrum resulting from an individual in the uncontaminated state is known, it is not easy to determine the amount of material contributing to the spectrum of the individual in the contaminated state. By using an empirical equation obtained from counting a known population of unexposed people, it is possible to predict the expected contribution due to Compton scattering in the spectrum of any individual [2]. It is therefore possible to estimate the spectrum of an individual in the uncontaminated condition, and to predict the count rate for the uncontaminated condition at the energies of 186 and 90 keV, if certain physical properties of the individual such as mass and length are known.

From the predicted spectrum in the uncontaminated state and the measured spectrum in the contaminated state, it is possible to determine the count rate due to the contaminating material. A comparison of the count rates in the 186 and 90 keV regions can reveal some information on the level of enrichment of uranium (Fig. 1). Correct calibration with uranium samples in phantoms is necessary to calculate the amount of material present. Reliable provision should be made for absorption due to chest tissue, bones and ribs.

In the absence of a low-background facility in which to do the counting, the contribution of external radiation to the respective count rates of exposed and unexposed individuals results in large uncertainties in the calculated count rates representing the actual contamination. Background spectra for three different experimental conditions are illustrated in Fig. 2. The data in Fig. 3 represent the average spectra for 10 individuals, each of whom was measured under all three experimental conditions. From Fig. 3 it is clear that the human spectra are vastly different for different background conditions. It is generally accepted that *in vivo* lung counting is not feasible if a low-background room (low curve in Figs. 2 and 3) is not available. In the discussion that

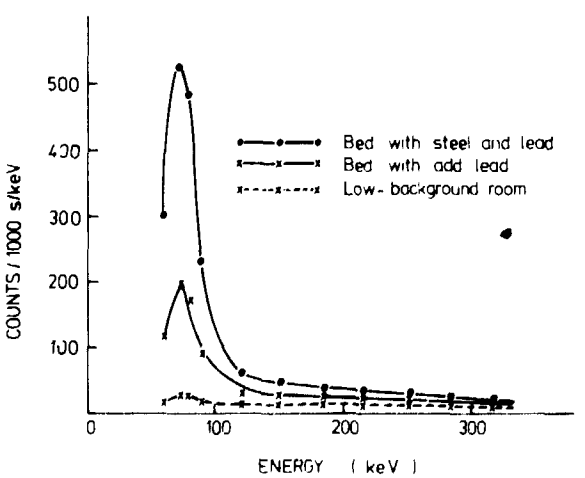

Fig. 2
Background spectra for three different conditions

follows, a method of analysis is suggested by means of which the amount of uranium present in the lungs can be determined under background conditions similar to those illustrated by the two higher curves in Fig. 2.

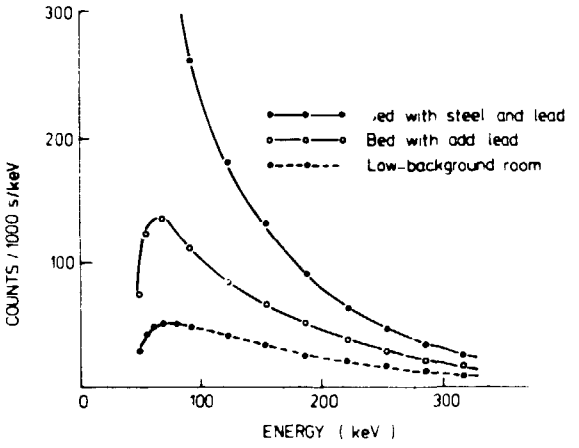

Fig. 3
Human spectra obtained under three different background conditions

3. THE GAMMA COUNTING FACILITY

A phoswich detector of 203 mm diameter was used, consisting of NaI (Tl) and CsI (Na) scintillation detectors of 12,5 mm and 50 mm thicknesses, respectively, hermetically sealed in a stainless steel housing with a 0,25 mm thick Al entrance window, and optically coupled to three 76 mm RCA-4524 photomultiplier tubes. A block diagram illustrating the electronic equipment is shown in Fig. 4. The pulse

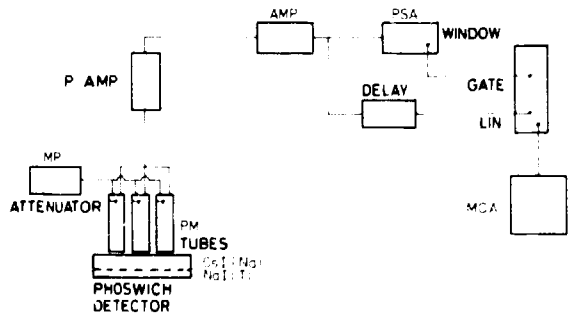

Fig. 4
Block diagram of electronic equipment

shape analyser, ORTEC 458, converts the decay period of the impulses to amplitude. The longer decay period of the impulses from the CsI (Na) detectors (0,63 μs average) then result as larger amplitude impulses than those from the NaI (Tl) detector (0,23 μs decay period). The output from the pulse shape analyser is illustrated in Fig. 5. Three distinctive sets of events can be distinguished, namely those where the radiation was totally absorbed in either the NaI or CsI crystal, and those where radiation was partially absorbed in either crystal and penetrated into the other resulting in simultaneous impulses from both crystals – indicated as coincidence events in Fig. 5. The pulse

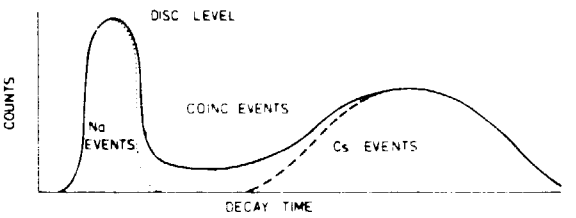

Fig. 5
Output from pulse shape analyser

discrimination was set in such a way that only those pulses formed in the NaI crystal were allowed to be registered by the multichannel analyser, and in this way most of the background noise was discriminated against.

This then limits the counting facility to energies below about 300 keV allowing the determination of the relevant uranium isotopes. It has the disadvantage, however, that the ^{40}K peak cannot be measured.

The *in vivo* counting facility was erected in an unshielded room and consisted of a movable bed, surrounded by 50 mm steel lined with 3 mm lead. The steel was specially selected for low radioactive content. The construction is illustrated in Fig. 6. A bridge suspended the phoswich detector (which was also shielded with similar thicknesses of steel and lead), with an additional Sb collar of 1 mm thickness around the phoswich crystal. The detector was in a fixed position whilst the bed with the patient could be lifted by means of a hydraulic cylinder to a position close to the detector (Fig. 7). A 12 mm thick collimator of low radioactivity steel was used in front of the detector. The spectra obtained with this facility are shown as the upper curve in Figs. 2 and 3.

In order to improve the background spectrum, additional lead shielding was added to the same facility described above. This bed with additional shielding as illustrated in Fig. 8, showed appreciable improvement in the background count as shown in Figs. 2 and 3.

The counting facility was also tested in a standard low-background room with 200 mm thick steel walls, floor and roof, used for the whole-body counter [8]. A 3 mm layer of lead was affixed to the inside of the steel walls and roof. The floor was also covered with 3 mm lead sheeting and finished with a PVC floor-covering material. The construction of the swinging door was similar to that of the walls. A small opening of 200 x 250 mm in one of the walls was used for communication to electronic equipment outside the room. The phoswich detector was suspended on a low-radiation steel frame which could be lowered onto the patient's chest.

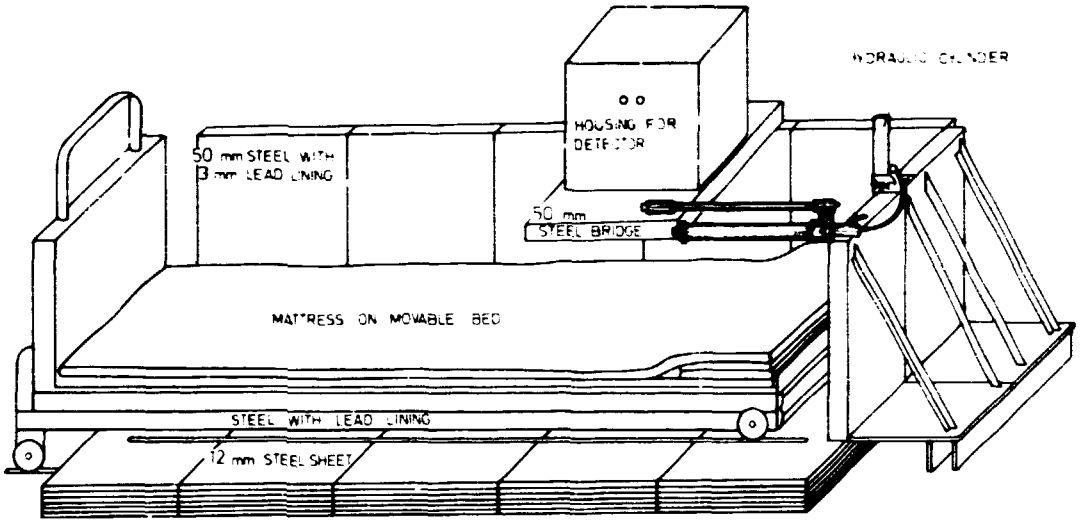

Fig. 6. Bed with local shielding

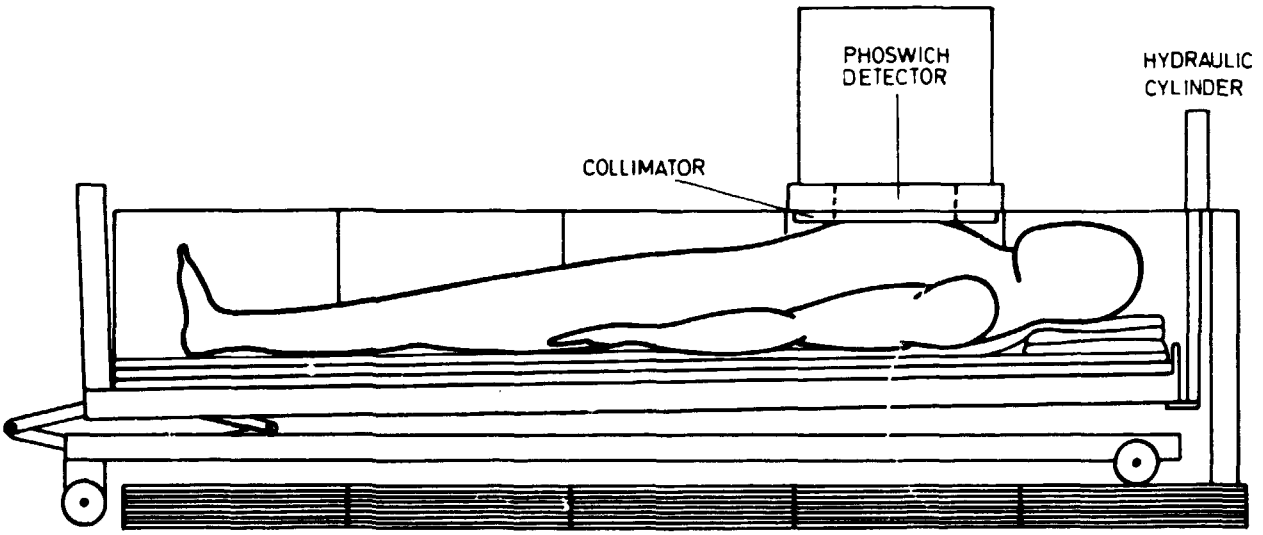

Fig. 7. Patient in counting position

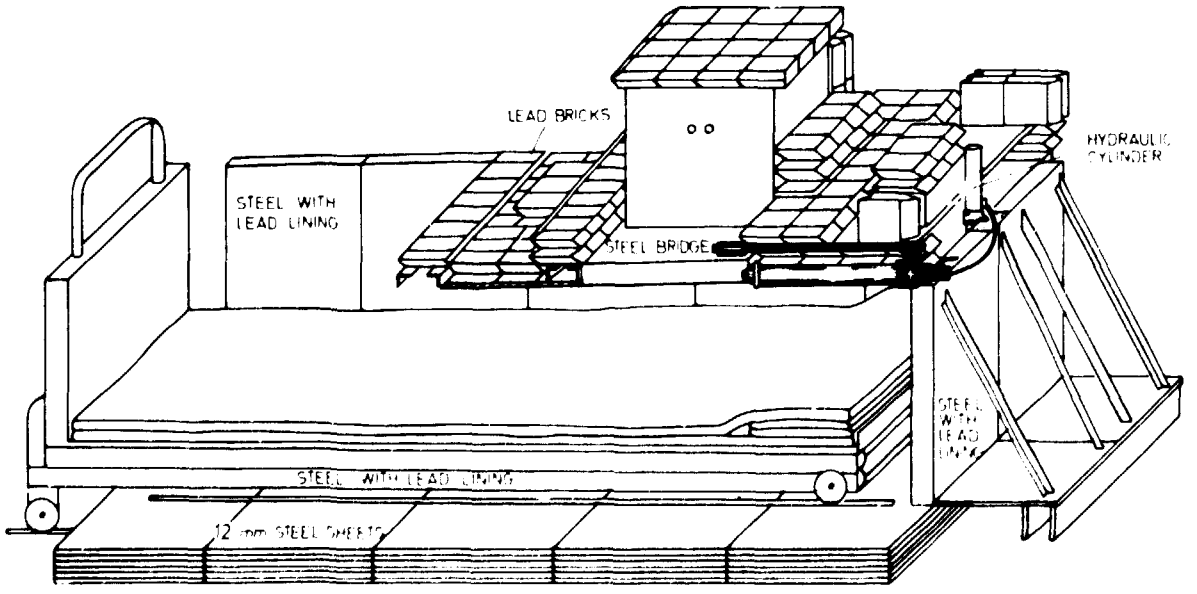

Fig. 8 Bed with local shielding plus additional lead

The background spectrum of lowest counts in Figs. 2 and 3 were obtained with this facility.

Since the methods of determining the amount of uranium contamination using a low-background room have been amply dealt with by other workers, as described in the Introduction, more attention was given to the conditions where only local shielding was used around the subject, i.e. relatively high-background conditions. These three conditions will be referred to as high, medium and very low backgrounds.

4. RESULTS AND DISCUSSION

4.1 Method of Analysis

A group of 17 uncontaminated people were measured under the three background conditions and spectra almost identical to those in Fig. 3 were obtained. For the energy range from 90 keV to 320 keV, eight regions, each 18 keV wide, were selected and the integrated count over each region determined (Fig. 9). The average number of counts

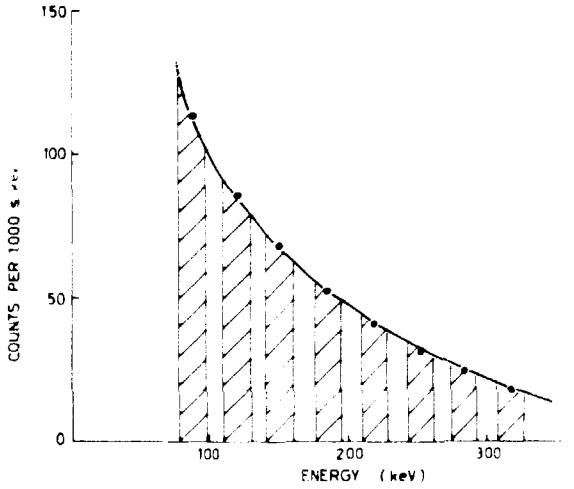

Fig. 9
Human spectrum with the energy regions indicated for which the integrated counts were determined

per keV for each energy region was calculated for the counting period of 1 000 s. The average count per keV per 1 000 s is referred to as N. If LnN is plotted against the energy E (keV), then a straight line is obtained, with a very high correlation coefficient. The data from each individual of the abovementioned group were analysed. The average correlation coefficient for the group for medium-background conditions was $\bar{r}_m = 0.999$ and for high-background conditions was $\bar{r}_h = 0.998$, and the poorest correlation coefficient for any individual was $r_p = 0.995$.

It appears therefore that under the conditions in which the experiment was carried out, a linear relationship between LnN and E is unique to all individuals. These results are illustrated in Fig. 10.

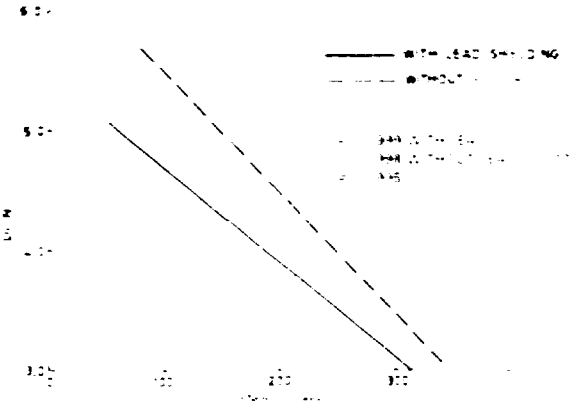

Fig. 10.
LnN against E for the human spectra obtained for the two high-background conditions

A further group of 20 unexposed people were used and the measurements repeated. Similar results were obtained, with the lowest correlation coefficient for any individual this time being $r_p = 0.990$. The slopes of the individual lines varied from −0.0075 to −0.0092 with an average of −0.0081 for the medium-background conditions, and from −0.0098 to −0.110 with an average of −0.0103 for the high-background condition.

From these results it is clear that larger backgrounds result in lines with steeper slopes and slightly poorer correlation coefficients, but the latter are still extremely good. It appears feasible, therefore, to detect the presence of foreign radioactivity in the body by observing a displacement of any point from the linear line. By calibrating the displacement with reference to known amounts of uranium, methods for the quantitative measurement of uranium and for the quantitative measurement of contamination can be established. Such a method is illustrated in Fig. 11.

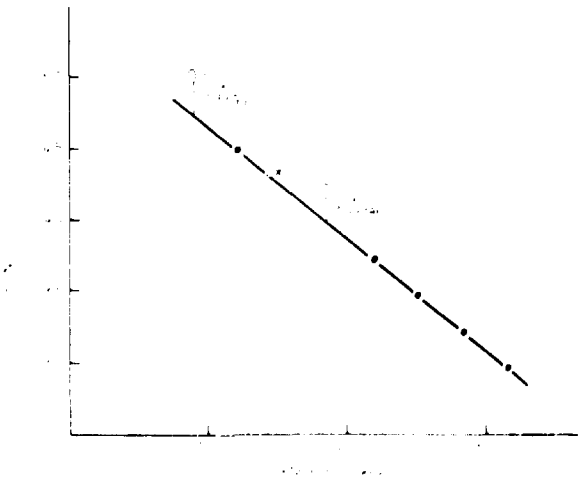

Fig. 11.
Determination of displacement values at 90 and 186 keV

In order to obtain data on the amount of radioactive material present in the chest of a potentially contaminated

person, the linear relationship has to be established. The individual is counted and a line is obtained from five representative count rates for five energy interval points. The displacements in 90 keV and 186 keV regions (Δ_{90} and Δ_{186}) give an indication of the amount of contaminating uranium material. The Ln of the actual counts measured at 90 keV and 186 keV are indicated as circles in Fig. 11. The reason why the third point (the cross in Fig. 11) is not included in obtaining the line is discussed in par. 4.4.

In order to determine the sensitivity and reliability of the method, it is essential to determine what the scatter will be in the value of Δ that normally occurs for unexposed individuals.

4.2 Normal Scatter Amongst Uncontaminated People

The data for the two groups of 17 and 20 uncontaminated people were used to obtain a linear relationship of LnN against E for each individual as calculated from five points, and then the displacements from the line for each of the eight points measured were calculated. The relevant data for medium-background conditions are shown in Table I, and that for high-background conditions in Table II. From Table I it

TABLE I

Displacement data from the individual straight lines where the lines have been obtained from five points. Medium-background conditions. The displacement values refer to LnN where N is the number of counts per 1 000 s.

	Energy regions (keV)	Mean energy (keV)	Mean (*) displacement of LnN ($\times 10^{-2}$)	Largest (*) displacement above line ($\times 10^{-2}$)	Largest (*) displacement below line ($\times 10^{-2}$)
Δ_1	81-98	90	+ 0,05	+ 8,1	- 6,0
Δ_2	113-130	122	- 1,5	+ 0,7	- 4,9
Δ_3	143-160	152	+ 0,6	+ 6,3	- 4,3
Δ_4	177-194	186	+ 0,3	+ 6,7	- 4,5
Δ_5	211-228	220	+ 1,2	+ 7,0	- 3,9
Δ_6	243-260	252	+ 3,0	+ 6,4	- 2,4
Δ_7	275-292	284	- 0,2	+ 7,1	- 5,2
Δ_8	307-324	316	- 2,4	+ 3,9	- 7,3

(*) The positive sign indicates that the measured point is above the calculated line and vice versa.

TABLE II

Displacement data from the individual straight lines where the lines have been obtained from five points. High-background conditions. The displacement values refer to LnN where N is the number of counts per 1 000 s.

	Energy regions (keV)	Mean energy (keV)	Mean (*) displacement of LnN ($\times 10^{-2}$)	Largest (*) displacement above line ($\times 10^{-2}$)	Largest (*) displacement below line ($\times 10^{-2}$)
Δ_1	81-98	90	+ 8,0	+ 11,0	-
Δ_2	113-130	122	+ 2,0	+ 3,4	- 0,5
Δ_3	143-160	152	- 0,5	+ 2,2	- 4,2
Δ_4	177-194	186	- 3,3	-	- 8,2
Δ_5	211-278	220	- 2,6	+ 0,5	- 6,5
Δ_6	243-260	252	- 2,5	+ 3,0	- 8,5
Δ_7	275-292	284	+ 0,3	+ 4,9	- 3,6
Δ_8	307-324	316	+ 2,7	+ 8,5	- 1,1

(*) The positive sign indicates that the measured point is above the calculated line and vice versa.

can be seen that the largest discrepancy for Δ_{90} is 8×10^{-2} above the line and 6×10^{-2} below the line, and for Δ_{186} it is 7×10^{-2} above the line and 5×10^{-2} below the line.

These values indicate the possible inaccuracy of the method, or the extent to which measured contaminations can be detected correctly. The displacements resulting from various amounts of uranium in the body to the straightline relationship were determined by means of the calibration procedure described below.

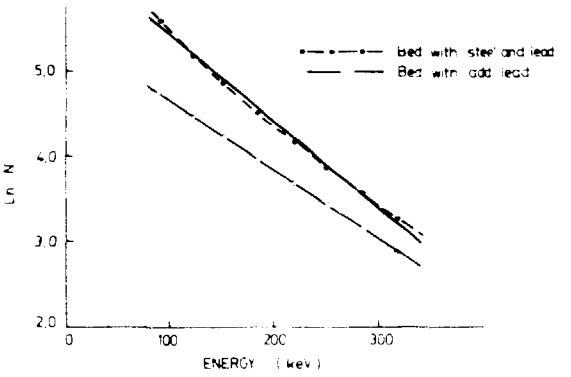

Fig. 12.
Average relationships of LnN against E for the two high-background conditions

The average values from 37 subjects for LnN against E have been plotted in Fig. 12. The data for medium-background conditions (lower line in Fig. 12) show that the straight line fits the data very well, but the data for high-background conditions (higher line in Fig. 12) tend to follow a slight curve as indicated by the dotted line. The solid line represents the average linear relationship. The displacements of the two middle points below the line and the two outer points above the straight line are, however, very small (i.e. an average LnN of $-3,5 \times 10^{-2}$ for the fourth point, $+5,1 \times 10^{-2}$ for the first point, and $+4,3 \times 10^{-2}$ for the eighth point). These values are much smaller than the normal scatter encountered for the measured population of unexposed people.

4.3 Calibration Procedure

It is important to have a reliable geometric simulation of the human chest for the purpose of calibrating the counting facility in terms of the amount of uranium contamination present. This simulation should make provision for the absorption that will take place in chest tissue, bone and ribs. Bogen *et al* [3] reported that the ribs, breastbone and vertebrae can be simulated by 3 mm thickness of aluminium, and the tissue by a layer of 20 mm thick paraffin wax. A phantom was constructed with the top layer consisting of 20 mm paraffin wax and 3,0 mm aluminium, with a supporting surface for uranium samples at a distance of 150 mm from the top. The average chest thickness of the 37 subjects measured was 260 mm, giving a half-depth of 130 mm. If the lungs are displaced somewhat further from the front and allowing for a further few mm that the chest surface will be from the collimator surface, due to the fact

that the chest surface is not perfectly flat, the estimated distance between the collimator surface and the midpoint of the lungs will be approximately 150 mm.

Samples of natural uranium were made up by diluting uranyl nitrate in distilled water and distributing it on a special blotting paper over an area of 180 x 240 mm. Care was taken to ensure an even distribution. This sample was then sandwiched between two thin sheets of polycarbonate. No significant radiation could be detected from the material that was used as sample holder. Measurements were then carried out with the phantom alone and the phantom plus samples containing various concentrations of natural uranium. The data are given in Table III, from which the equivalent Δ_{90} and Δ_{186} values for any particular amount of uranium can be obtained.

4.4 Determination of Uranium Contamination in the Lungs

The count data obtained from a subject are used to obtain a linear relationship. The count rates for the five relevant energy regions are used as described in par. 4,1, and a straight line is fitted through the points by a simple computer calculation, the program for which is given in Appendix A. The displacements of the points in the Δ_{90} and Δ_{186} keV regions from this linear relationship are obtained from the same calculation. These displacement data are then compared with the calibration data in Table III to determine the amount of uranium present in the area of measurement.

TABLE III

CALIBRATION LEVELS OF CONTAMINATION FOR NATURAL URANIUM

Multiples of MPLB	Amount of uranium (mg)	Deviation from straight line (Δ LnN)	
		Δ for 90 keV	Δ for 186 keV
1	25,6	28×10^{-2}	19×10^{-2}
¾	19,4	24×10^{-2}	14×10^{-2}
½	12,6	14×10^{-2}	10×10^{-2}
99 % confidence limits		$4,5 \times 10^{-2}$	$6,7 \times 10^{-2}$

Largest scatter of any individual amongst 37 "uncontaminated" people

$$\Delta^{\circ}_{90} \quad +8 \times 10^{-2} \quad -6 \times 10^{-2}$$

$$\Delta^{\circ}_{186} \quad +7 \times 10^{-2} \quad -5 \times 10^{-2}$$

Several factors can influence the accuracy of this determination. The normal scatter in the values of Δ_{90} and Δ_{186} that occur for different individuals will limit the accuracy of the determination, and the level of enrichment of the uranium that caused the contamination will result in different relative values of the displacements at 90 keV and 186 keV. These limitations will be discussed in the following paragraph. Another important factor that can contribute largely to the count rate, is surface contamination on the skin of the subject. Spitz *et al* [6] took care of this problem by measuring the 16 keV X-rays by means of phoswich detectors, in addition to the 90 and 186 keV gammas. If these soft 16 keV X-rays are present, it is a sure indication of the presence of contamination on the skin of the subject. By means of calibration it was then possible to correct the measured data for the contribution from skin contamination. A low-background counting room is needed for this approach.

In the absence of a low-background room, external contamination was measured with a sensitive alpha counter. When surface contamination is present, the uranium on the skin is in almost direct contact with the phoswich detector during the counting of the patient. The gamma count rate contribution from a small quantity of uranium on the skin will be appreciably higher than that for an equal quantity of uranium present in the lungs. In order to correct for the contribution of the measured amount of skin contamination, it was necessary to express the alpha counts from the surface contamination in terms of the equivalent gamma contribution to the phoswich detector originating from a certain amount of uranium in the lungs. This equivalent gamma contribution was then subtracted from the N-value originally obtained for the patient. This calibration was done using a phantom.

A further factor that requires attention is the absorbing thickness of the chest. As already described, 3 mm Al and 20 mm paraffin wax was used to simulate the average chest wall thickness. The influence of this absorbing material is illustrated in Fig. 13. In order to determine the amount of uranium in a subject, it is necessary to know the variation in the chest of the subject from that of the average, and also the influence of this difference on the count rate. It is usual to determine the chest wall thickness by means of ultrasound equipment [9, 10, 11]. This was however not available in our study and the correction for changing chest dimensions has still to be studied.

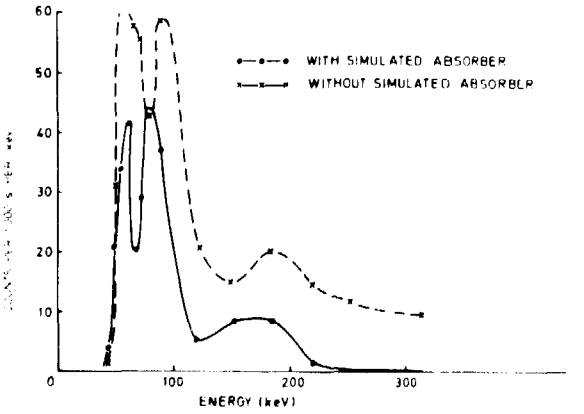

Fig. 13

The effect of absorbing material on the shape of the uranium spectrum for one MPLB

From Fig. 13 it is clear that the count rate is significantly decreased by the absorbing material, and that the shape of the two peaks is affected by Compton scattering. The point at 152 keV which was well clear from the 186 keV peak when no absorber was used, is no longer resolved when the absorbing material is used. Due to the Compton scattering

the point at 122 keV was also slightly affected. A slight correction of this point (which is also used to obtain the linear relationship) is required to improve the accuracy of the procedure. The procedure to determine the linear relationship as described above is therefore altered slightly. During calibration experiments it was found that Δ_{122} is about 75 % of Δ_{186} for contamination levels up to 1 MPLB. Therefore, the linear relationship was obtained as before, the value of Δ_{186} was then obtained and then the value of LnN for 122 keV was reduced by an amount equal to 75 % of Δ_{186} and Δ_{90} which can be used to obtain the amount of uranium present in the chest from Table III. This variation was built into the program of calculation. (Appendix A).

4.5 Limitations on the Accuracy of the Method

From Table III it can be seen that the equivalent value of Δ_{90} for ½ MPLB is 14×10^{-2}. The largest scatter above the straight line obtained for any individual amongst the 37 uncontaminated people measured was 8×10^{-2} for 90 keV. It is therefore clear that the value for ½ MPLB is significantly above the largest single scatter. Similarly, the maximum scatter at 186 keV was 7×10^{-2}. These maximum values of the individual scatter did not occur at both the energy levels of 90 and 186 keV for the same person. It is therefore obvious that the resolution of the method is much better than ½ MPLB. More work has to be done to determine the actual accuracy, but it is expected to be between ¼ MPLB and 1/3 MPLB. This can still be improved further by increasing the counting period.

The maximum scatter obtained for any one individual amongst the 37 unexposed people was used to determine the sensitivity of the method rather than the 99 % confidence limits, because it is a single individual who is under examination when a measurement is carried out. For the sake of comparison, the 99 % confidence limits are also included in Table III. If this is taken as the criterion for determining the sensitivity of the method, then the expected resolution improves.

The level of enrichment of the uranium determines the relative magnitudes of the peaks at 90 keV and 186 keV as illustrated in Fig. 1. If the enrichment level is known, then both of the peaks can be used to determine the amount of ^{235}U, and the 90 keV will reveal some information on the amount of ^{238}U present. Since the two daughters of ^{238}U and ^{235}U (^{234}Th and ^{231}Th respectively) both contribute to the 90 keV peak but at slightly different energy levels (93 keV and 84 keV respectively), it will be necessary to distinguish between these two contributions. In our case the largest contribution comes from the ^{234}Th, which is indicative of the amount of ^{238}U present. Calibrations as illustrated in Table III refer to natural uranium only. Further calibrations are being carried out for low-enrichment levels.

5.CONCLUSIONS

While *in vivo* lung counting is normally carried out in a very low-background room, it is possible to do acceptable measurements under higher background conditions. Due to the fact that contamination levels of between ½ and one MPLB are of particular importance in routine measurements, it is preferable that such a counting facility should be able to detect contaminatin levels as low as ½ MPLB. By means of the method of analysis suggested in this publication, it is possible to detect contamination levels of ½ MPLB or slightly lower. This applies for a counting period of 1 000 s, which is acceptable for routine measurements. The counting period can be increased in individual cases if required to improve statistics.

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C                                   IN-VIVO URANIUM MONITORING
C
C       AJST - A PROGRAM TO DETERMINE THE LN(COUNTS/KEV) VERSUS ENERGY
C       LINEAR LINE, I.E. SLOPE, INTERCEPT AND REGRESSION COEFFICIENT
C       THROUGH THE SECOND AND FIFTH TO EIGHTH DATA POINTS OF EIGHT DATA
C       POINTS, SUBTRACT 75% OF THE POSITIVE DEVIATION OF THE FORTH DATA
C       POINT FROM THE SECOND DATA POINT AND RECALCULATE THE SLOPE, INTERCEPT,
C       REGRESSION COEFFICIENT AND DEVIATIONS FOR A NUMBER OF OBSERVATIONS
C
C       INPUT DATA AND FORMATS
C
C       FOR EACH OBSERVATION READ
C       B(ICOUNT,J)-NO OF COUNTS IN THE JTH CHANNEL (J=1 TO 8) FOR THE ICOUNT-TH OBSERVATION
C       FORMAT(8F10.0)
C       THE LAST OBSERVATION IS FOLLOWED BY A BLANK CARD
C
0001            IMPLICIT REAL*8 (A-H,O-Z)
0002            REAL*8 MEAN,INTER
0003            DIMENSION B(40,8),Y(8),SUM(8),MEAN(8),SLOPE(40),REGRE(40),INTER(40),DELTA(40,8),X(8),K(8)
0004            DATA Y/90.,122.,152.,186.,220.,252.,284.,316./
0005            NSTEP=0
0006            ICOUNT=1
C
C       READ THE 8 NO OF COUNTS PER CHANNEL FOR THE ICOUNT-TH OBSERVATION
C
0007          5 READ(5,400)(B(ICOUNT,J),J=1,8)
C
C       A BLANK CARD MEANS THE END OF THAT SET
C
0008            IF(B(ICOUNT,1).EQ.0.0)GO TO 10
C
C       NORMALISE THE NO OF COUNTS PER CHANNEL WITH 18 KEV PER CHANNEL
C
0009            DO 7 J=1,8
0010          7 B(ICOUNT,J)=B(ICOUNT,J)/18.0
0011            ICOUNT=ICOUNT+1
0012            GO TO 5
0013         10 CONTINUE
0014            ICOUNT=ICOUNT-1
C
C       CONVERT DATA TO LOG FORM
C
0015            DO 15 I=1,8
0016          5 SUM(I)=0.0
0017            DO 20 I=1,ICOUNT
0018            DO 20 J=1,8
0019            SUM(J)=B(I,J)+SUM(J)
0020            B(I,J)=DLOG(B(I,J))
0021         20 CONTINUE
0022            DO 22 J=1,8
0023         22 K(J)=Y(J)
0024         25 CONTINUE
0025            IF(NSTEP.EQ.2)GO TO 999
0026            IF(NSTEP.EQ.1)WRITE(6,480)
C
C       CALCULATE SLOPE, INTERCEPT AND REGRESSION COEFFICIENTS
C
0027            S=0.
0028            SUM1=0.0
0029            SUM2=0.0
0030            DO 30 I=1,8
0031            IF(I.EQ.1.OR.I.EQ.3.OR.I.EQ.4)GO TO 30
0032            S=S+1.
0033            SUM1=SUM1+Y(I)
0034            SUM2=SUM2+Y(I)**2
0035         30 CONTINUE
0036            BOT1=SUM2-SUM1**2/S
0037            XAV=SUM1/S
0038            DO 40 I=1,ICOUNT
0039            SUM3=0.0
0040            SUM4=0.0
0041            SUM5=0.0
0042            DO 35 J=1,8
0043            IF(J.EQ.1.OR.J.EQ.3.OR.J.EQ.4)GO TO 35
0044            SUM3=SUM3+B(I,J)
0045            SUM4=SUM4+B(I,J)**2
0046            SUM5=SUM5+B(I,J)*Y(J)
0047         35 CONTINUE
0048            YAV=SUM3/S
0049            TOP=SUM5-SUM3*SUM1/S
```

```
0050                BOT=SUM4-SUM3**2/S
0051                SLOPE(I)=TOP/BOT1
0052                INTER(I)=YAV-SLOPE(I)*XAV
0053                REGRE(I)=TOP**2/(BOT*BOT1)
0054          40    CONTINUE
            C
            C       WRITE OUT THE LN OF THE NORMALISED COUNTS, SLOPES, INTERCEPTS,
            C       REGRESSION COEFFICIENTS AND DEVIATIONS OF THE POINTS FROM THE LINE
            C
0055                WRITE(6,440)
0056                WRITE(6,470)(K(I),I=1,8)
0057                WRITE(6,430)((B(I,J),J=1,8),I=1,ICOUNT)
0058                WRITE(6,410)
0059                WRITE(6,420)(SLOPE(I),INTER(I),REGRE(I),I=1,ICOUNT)
0060                WRITE(6,450)(K(I),I=1,8)
0061                DO 47 J=1,8
0062          47    SUM(J)=0.0
0063                DO 50 I=1,ICOUNT
0064                DO 48 J=1,8
0065                X(J)=SLOPE(I)*Y(J)+INTER(I)
0066                DELTA(I,J)=B(I,J)-X(J)
0067                SUM(J)=SUM(J)+DELTA(I,J)
0068          48    CONTINUE
0069                WRITE(6,430)(DELTA(I,J),J=1,8)
0070          50    CONTINUE
0071                DO 55 J=1,8
0072                MEAN(J)=SUM(J)/FLOAT(ICOUNT)
0073          55    CONTINUE
0074                WRITE(6,460)(MEAN(J),J=1,8)
0075                DO 80 I=1,ICOUNT
            C
            C       IF THE DEVIATION AT THE FORTH POINT IS GREATER THAN ZERO SUBTRACT
            C       75% OF THE 4TH DEVIATION FROM THE 2ND POINT
            C
0076                IF(DELTA(I,4).LE.0.0)GO TO 80
0077                B(I,2)=B(I,2)-DELTA(I,4)*.75
0078          80    CONTINUE
0079                NSTEP=NSTEP+1
            C
            C       RECALCULATE SLOPES, INTERCEPTS, REGRESSION COEFFICIENTS AND
            C       DEVIATIONS OF THE POINTS FROM THE LINE
            C
0080                GO TO 25
0081        999     CONTINUE
0081        400     FORMAT(8F10.0)
0083        410     FORMAT(/3X,'SLOPE',15X,'INTERCEPT',11X,'REGR.COEF.'/)
0084        420     FORMAT(3(1X,E10.4,10X))
0085        430     FORMAT(8(1X,E10.4,2X))
0086        440     FORMAT(' LN(COUNTS/KEV)'/)
0087        450     FORMAT(/' ',8('DELTA-',I3,4X)/)
0088        460     FORMAT(/' DELTA MEANS'//8(1X,E10.4,2X)/)
0089        470     FORMAT(1X,8(1X,I3,1X,'KEV',5X)/)
0090        480     FORMAT(' ADJUSTED VALUES'/)
0091                END
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