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AN EXPERIMENTAL EVALUATION OF MULTIPLE-CRYSTAL ARRAYS AND SINGLE-CRYSTAL TECHNIQUES *

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Abstract — Résumé — Аннотация — Resumen

An experimental evaluation of multiple-crystal arrays and single-crystal techniques. This study was undertaken to ascertain the sensitivity of various geometries in human body counters and to evaluate the uncertainties arising in each case from the use of an average calibration factor in people of the same height and weight, but differing in other anatomical characteristics.

The following measuring techniques were used with a single crystal: (*a*) the 175-cm-arc technique, (*b*) the "Tilting Chair" technique, (*c*) the crystal at the small of the back, and (*d*) a crystal under the chair of a seated person. In addition, various multiple-crystal arrays were evaluated by placing in turn, a single crystal at 7 equally spaced points 10 in apart along the body, at each of two heights above and two distances below the supine subject.

The gamma-ray spectra of a group of 20 patients, containing known quantities of K^{42}, and a group of 12 patients, containing Ra^{226}, were obtained. The counting-rate from each subject, corrected for excretion and decay in the case of K^{42}, was compared with the average for the group to determine the magnitude of the variations that existed between subjects of different body builds. To evaluate further the calibration problems involved in each array the subject's spectra were compared with the spectra obtained with known amounts of the same isotope in various phantoms.

Although with a multiple-crystal array greater sensitivities are possible than with the tilting chair, the uncertainty involved is about twice that obtained with the tilting chair or the 175-cm arc. This uncertainty can be eliminated by administering to each person a known tracer dose; however, this may not always be feasible and should be avoided, since it increases considerably the technical difficulties.

Evaluation expérimentale d'ensembles à plusieurs cristaux et méthodes de mesure avec un cristal unique. Cette étude a été entreprise pour déterminer la sensibilité de certaines géométries des compteurs de l'activité du corps humain et évaluer les incertitudes résultant, dans chaque cas, de l'utilisation d'un facteur d'étalonnage moyen pour des individus de même taille et de même poids mais dont les autres caractéristiques anatomiques diffèrent.

L'auteur a utilisé les méthodes de mesure suivantes, avec un seul cristal : *a*) méthode de l'arc de 175 centimètres, *b*) méthode de la chaise à bascule, *c*) cristal placé dans le creux des reins et *d*) cristal placé sous la chaise de la personne assise. De plus, il a étudié le comportement de plusieurs ensembles à cristaux multiples en plaçant un cristal unique en 7 endroits successifs distants de 10 pouces les uns des autres (25 cm environ) et situés, dans l'axe du corps en supination, sur quatre plans horizontaux, deux au-dessus et deux en dessous du sujet.

L'auteur a obtenu les spectres de rayons gamma d'un groupe de 20 patients dont l'organisme contenait des quantités connues de ^{42}K et d'un groupe de 12 patients dont l'organisme contenait du ^{226}Ra. Il a comparé le taux de comptage enregistré pour chaque sujet, corrigé pour tenir compte

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de l'excrétion et de la désintégration dans le cas de ^{42}K, au taux moyen enregistré pour le groupe, afin de déterminer l'importance des écarts existants entre des sujets de constitutions différentes. Pour évaluer de façon plus approfondie les problèmes d'étalonnage posés pour chaque ensemble, l'auteur a comparé les spectres des sujets aux spectres obtenus à partir de quantités connues du même isotope existant dans divers fantômes.

Le système à cristaux multiples permet d'obtenir des sensibilités plus grandes que la méthode de la chaise à bascule mais le degré d'incertitude est environ le double de celui qu'on enregistre avec cette méthode ou celle de l'arc de 175 cm. On peut éliminer cette incertitude en administrant à chaque individu une quantité donnée d'élément marqué; cependant, ceci n'est pas toujours possible et doit être évité car les difficultés techniques s'en trouvent considérablement accrues.

Экспериментальная оценка методов использования многокристальных и однокристальных систем. Это исследование было предпринято с тем, чтобы установить чувствительность различных геометрий счетчиков активности человеческого организма и оценить неточности, возникающие в каждом случае в связи с использованием среднего коэффициента калибровки у людей, имеющих одинаковый рост и вес, но отличающихся по другим анатомическим характеристикам.

Следующие методы измерения использовались с монокристаллом: a) метод дуги 175 см, b) метод «поворачивающегося кресла», c) кристалл на пояснице и d) кристалл, расположенный под креслом, на котором сидит человек. Кроме того, оценивались различные системы счетчиков с несколькими кристаллами, помещая по очереди монокристалл в 7 равно отстоящих друг от друга местах на расстоянии 10 дюймов вдоль тела, причем каждый раз кристалл размещался на двух расстояниях вверх и двух расстояниях вниз от лежащего человека.

Были получены спектры гамма-излучения группы из 20 пациентов, содержащих известное количество калия-42, и группы из 12 пациентов, содержащих радий-226. Скорость счета у каждого пациента, с коррекцией на выделение и распад в случае калия-42, сравнивалась со средним значением для группы с тем, чтобы определить величину отклонений, существующих между пациентами с различным телосложением. Далее, для оценки проблем калибровки, связанных с каждой системой счетчиков, спектры объектов сравнивались со спектрами, полученными с известным количеством того же изотопа в различных фантомах.

Хотя при системе счетчиков с несколькими кристаллами можно получить большую чувствительность, чем с поворачивающимся креслом, присущая этой системе неточность примерно в два раза превышает неточность при поворачивающемся кресле и дуге в 175 см. Эту неточность можно устранить, введя каждому пациенту известную дозу индикатора, однако это не всегда осуществимо и этого следует избегать, поскольку значительно увеличиваются технические трудности.

Una evaluación experimental de los aparatos de cristal múltiple y de las técnicas a base de un solo cristal. El autor emprendió este estudio con el propósito de determinar la sensibilidad de las diversas geometrías de los contadores de la actividad del cuerpo humano y de evaluar la indeterminación a que da lugar, en cada caso, el empleo de un factor de calibración medio para individuos de igual estatura y peso, pero que se diferencian por otras características anatómicas.

Se aplicaron los siguientes métodos de medición, con cristal único: *a*) el método del arco de 175 cm, *b*) el método de la "silla basculante", *c*) el método del cristal en la región lumbar, *d*) el método del cristal colocado debajo de la silla del paciente. Además, se analizaron varias disposiciones de cristales múltiples colocando, sucesivamente, un cristal en siete lugares equidistantes, con una separación de 10 pulgadas (254 mm), a lo largo del cuerpo, a dos diferentes alturas por encima del sujeto en posición supina y a dos diferentes distancias debajo del mismo.

El autor obtuvo el espectro de rayos gamma de un grupo de 20 pacientes cuyo organismo contenía cantidades conocidas de ^{42}K y de un grupo de 12 pacientes con ^{226}Ra. Comparó el índice de recuento correspondiente a cada sujeto, una vez introducida la corrección para tener en cuenta la excreción y desintegración en el caso del ^{42}K, con el índice medio del grupo, a fin de determinar la magnitud de las variaciones existentes entre sujetos de diferente contextura física. Para estudiar

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más a fondo los problemas de calibración planteados por cada disposición, comparó los espectros correspondientes al sujeto con aquellos que se registran con cantidades conocidas del mismo isótopo en varios maniquíes.

Si bien la disposición de cristales múltiples permite alcanzar sensibilidades más elevadas que el método de la silla basculante, el grado de indeterminación es aproximadamente el doble del que resulta del uso de la silla basculante o del arco de 175 cm. La indeterminación se puede eliminar administrando a cada persona una dosis conocida de indicador: pero ello no siempre es factible y, en general, conviene evitarlo, ya que acrecienta considerablemente las dificultades técnicas.

Introduction

Any measurement of the radioactive content of a human, regardless of the type of human counter, will contain an inherent uncertainty because internal absorption and scattering of the gamma rays is unavoidably greater in some subjects than in others. The magnitude of this inherent uncertainty will depend on the type of counting system, because body build and the location of the isotope within the body will make more difference in some systems than in others. This report evaluates this inherent uncertainty by comparing the results obtained on the same subjects with several types of gamma-ray spectrometer.

Different-sized crystals are used with some of the counting systems so that the sensitivity (detected counts/min per μc in the body) of counters that employ arrays of either small or large crystals can be compared with those that use single large crystals.

Criteria for the design of a practical human whole-body counter

Whether a total-body counter is designed to provide high sensitivity but relatively poor accuracy or high accuracy but poor sensitivity will depend upon its ultimate use. The first class of counter would be selected to measure, for example, the natural radium content of large populations. Accuracy in an individual measurement would not be important, while sensitivity would be essential, because of the small amount of radium present and the great number of people to be measured. The second class of counter would be used in studying human metabolism of administered isotopes, etc. The emphasis in all discussions in this paper will be on accuracy, sensitivity being of only secondary interest.

If reliable and reproducible total-body measurements are to be made, a counter should be designed to satisfy the following specifications, listed in the order of importance.

(1) The sensitivity of the counter should not depend upon the subject's body build or upon the distribution of the material within his body. This is very important, since actually no radioactive material is uniformly distributed throughout the body. Even the normally occurring potassium is distributed differently in two subjects of the same size and weight. While it may be practicable to administer tracer quantities of short-lived isotopes to a limited number of subjects to calibrate the counter initially, administering a tracer to each and every subject is too expensive in both time and effort.

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(2) It should be possible to calibrate the counter with reasonable accuracy by using an appropriate phantom, since it is not feasible to administer tracer quantities of long-lived isotopes (e. g., alkaline earths) to humans. This requirement, when analysed, is basically a restatement of the first specification. In general, a phantom loaded with radioactive sources can only roughly approximate the actual distribution within the body. Also, since the same calibration is used for all subjects, any dependence of the counting-rate on distribution definitely introduces an error into each human measurement.
(3) The sensitivity (number of counts detected per μc in the body) should be high, in order to minimize counting times.
(4) The position of the subject and of each crystal should be the same for all total-body measurements, regardless of the subject's body build. An unassessable error will result if the technician is required to judge the optimum placement on the detectors for each subject. Furthermore, experience has demonstrated that it is advisable, if possible, to keep the detectors entirely unmoved, unless some positive mechanical arrangement is used to lock the crystal into exactly the same position each time it is replaced. Since errors from incorrect crystal placement are not detected by the routine checks of the equipment and since it may not be possible to repeat a measurement at a later date, it is false economy to use a crystal holder that does not lock precisely into the standard positions.
(5) Naturally the counter should have such other properties as good energy resolution (so that the various isotopes present can be identified), good energy stability and low gamma-ray background.

The first specification listed is the most important. Unfortunately, it is not possible to determine theoretically the degree to which a counting system satisfies it. This can be determined experimentally by using the counter to measure a large group of subjects who contain known amounts of radioactivity.

Whole-body counting techniques evaluated

General description

In order to evaluate the inherent uncertainty present in the measurements made with different types of whole-body human spectrometer, each type was used to measure (*a*) a group of 28 patients who contained known amounts of K^{42}; and (*b*) a group of 10 patients who had received radium-226 intravenously 30 years earlier. These two groups of patients were chosen because potassium, an alkali metal, concentrates mainly in the muscle mass of the body and radium, an alkali earth, concentrates in the skeleton. Obviously, the distribution of these two elements within the body will be quite different. A considerable collection of data is given in tabular form in order to provide interested persons with at least some experimental data that may be used as a guide in the future. These data are particularly valuable because the same subjects were measured with various techniques. Thus, when measurements made with one technique demonstrate large inherent uncertainties that were not present in measurements made with other techniques, these uncertainties can definitely be attributed to a property of that counter technique.

The various relative positions of patient and crystals will be described first. The gamma-ray spectra of the patient were obtained (*a*) with the "tilting chair" technique,

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(*b*) with the 1.75-m-arc technique, (*c*) with a 3-in × 5-in NaI(Tl) crystal at the small of the back, (*d*) with a different 3-in × 5-in NaI(Tl) crystal mounted under the seat of the tilting chair, and (*e*) with NaI(Tl) crystals of various sizes located at different points along the patient. Each subject was measured in the "tilting chair" and with at least one other technique.

Tilting-chair technique

This technique has been discussed in the literature [1]. Briefly, the patient sits in a typical position relative to the chair, but the chair is tipped backward so that the back of the chair is 35° from the horizontal. A NaI(Tl) crystal is placed above the chair, approximately over the patient's trochanter. The height of the crystal is adjusted so that the perpendicular distances from the back of the chair to the centre of the face of the crystal and from the seat of the chair to the face of the crystal are 42 cm. The dimensions of the crystals so used were (diameter × height): 4 in × 4 in, 8 in × 4 in, 9 in × 4 in and 11.5 in × 4 in.

3-in × 5-in NaI(Tl) crystal at the small of the back

A 3-in × 5-in NaI(Tl) crystal was mounted behind the back of the "tilting chair" discussed above. The axis of the crystal was parallel to the patient's spine and was placed 14 cm from the back surface of the patient. The bottom of the crystal was 21 cm and the top was 34 cm above the plane of the chair seat. The distance from patient to crystal was well established and reproducible, since the gamma-ray measurements were made with the chair tilted.

3-in × 5-in NaI(Tl) crystal under the seat

Another 3-in × 5-in NaI(Tl) crystal was mounted under the seat of the tilting chair. The axis of the crystal was set at right-angles to the patient's femora and tibia, 16 cm below the seat of the chair and 14 cm from the calf of the leg. The positions of the crystals for the three techniques discussed above are shown in Fig. 1.

1.75-m-arc technique

An 8-in × 4-in NaI(Tl) crystal was suspended 2 m above the floor in the centre of human spectrometer No. 2. The patient was placed first in a supine and then in a prone position on an air mattress that was supported on an arc of 1.75-m radius in such a fashion that the distal surface of the patient is 1.75 m from the centre of the crystal face. (See Fig. 2.) The patient's arms lie at his sides. The distal surfaces of the patient's head, chest, stomach, arms, thighs and feet are all at the same distance from the crystal. The gamma rays emerging from these volumes are counted with the same efficiency, independent of the subject's height.

The measurements made with this arrangement are considered to be absolute in the sense that variations in counting-rates per microcurie in the body can be attributed to intrinsic differences in internal absorption and scatter in the patient.

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Fig. 1
Experimental set-up illustrating three of the crystal-to-subject arrangements discussed in this paper

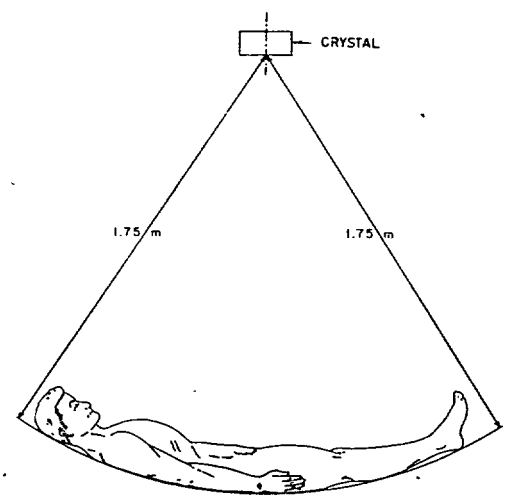

Fig. 2
Schematic representation of the crystal-subject arrangement in the 1.75-m-arc technique

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MULTIPLE-CRYSTAL ARRAYS

Type one

A series of measurements was made with a single 9-in × 4-in NaI(Tl) crystal located at various positions along the patient's body in order to synthesize the spectrum that would be obtained with a multiple-crystal array. (See Fig. 3.) The subject

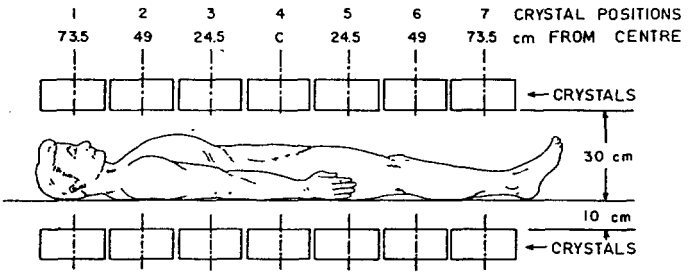

Fig. 3
Schematic illustration of the various locations at which the crystal was placed relative to the body in order to evaluate the merits of a multiple-crystal array

was placed on an air mattress supported by a thin metal bed, first in a supine and then a prone position. The face of the crystal was positioned over the mid-line of the patient and 30 cm above the surface of the bed for one series of measurements and 40 cm above the surface of the bed for the second series. The crystal was located at seven equally spaced points 24.5 cm apart along the length of the patient. The patient was placed so that the centre crystal was exactly half-way from the top of his head to his malleolus lateralis (ankle bone). In keeping with the philosophy that the technician should not select the crystal positions to correspond to the height of each subject, the crystals were used in the same positions for all patients.

After taking the spectra at each crystal position with the subject in a supine position and the crystal above him, the subject was then placed in a prone position and the gamma-ray spectra were obtained at these same 14 positions over his back.

Type two

The response of an array of crystals under the bed with the patient supine would differ from that obtained with an array over the prone patient. When the patient is in the prone position with the crystals above him, the distance from crystal face to patient varies from crystal position to crystal position. With the patient supine and the crystals set at a fixed distance under the bed, all crystal faces would be the same distance from the proximal body surface, since the position of the back surface of the patient is fixed by the surface of the bed. In order to determine whether a combination of crystals above and below the subject might yield a counting-rate that would be independent of the subject's thickness, the following series of measurements was made.

The thin metal bed was replaced with a sheet of lucite 0.75 in (1.9 cm) thick. The patient was placed in a supine position directly on the lucite. The air mattress

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and air pillows were eliminated so that the subject's position was fixed. Appropriate lines were scribed on the lucite to aid in lining up the crystals and the patient.

The 9-in × 4-in NaI(Tl) crystal was placed at the same seven positions lengthwise along the subject, 30 cm and 36 cm above the subject and 10 cm and 20 cm below. All distances were measured from the top surface of the lucite to the face of the crystal.

Measurements were made at the positions 30 cm above two patients with a 4-in × 4-in crystal, an 8-in × 4-in crystal and an 11.5-in × 4-in crystal.

Only one crystal was used for the above measurements because using four crystals simultaneously would have required either (1) mixing the four outputs with a mixer circuit and then sorting the pulses into a single composite spectrum, with the result that the individual spectra would have been lost; or (2) it would have been necessary to use the appropriate circuit (which is built into the analyser) to sort the output of each crystal into a different quarter of the memory of the analyser. The electronic difficulties of matching the resolution of four individual crystals and of calibrating the four crystals were avoided by using the single crystal. More reliable data were obtained by making a series of measurements with the same crystal and then, in the case of K^{42}, correcting the magnitude of each spectrum for radioactive decay over the time interval of the measurements.

Treatment of data

The pulses from the NaI(Tl) crystal and photomultiplier were amplified and sorted according to pulse height with a 256-channel magnetic-memory type of pulse-height analyser. The gain of the analyser was adjusted so that the 256 channels covered the energy span from 0 to 3.175 MeV. Each channel was thus 12.4 keV wide. After each measurement was completed, the data accumulated in the magnetic memory were punched, one channel at a time, into conventional seven-channel paper tape used with computers. The data on the punched tapes were then analysed by the Argonne National Laboratory computer called "George".

The computer was programmed to divide the data on the punched tape by the length of time of the measurement in order to obtain the counting-rate, then to subtract the background, and finally to print out the integrated number of counts that occurred in any selected groups of channels. When discussing K^{42} data, this paper will refer only to the integrated net counts in the two energy bands used to calculate a subject's normal K content. The counts in the channels that covered the energy band from 775 keV to 1.275 MeV were used, since these counts represent scattered K^{40} and K^{42} photons. The counts in the channels that covered the energy band from 1.375 MeV to 1.625 MeV were used to measure the primary gamma rays from K^{42} (1.52 MeV); and an energy band from 1.325 MeV to 1.575 MeV was used when measuring the subject's net K^{40} (1.46 MeV). The net counts in each group were corrected (by use of a hand calculator) for the subject's excretion and for the decay of K^{42} so that the data of one subject could be compared to another.

Four energy bands were used when analysing the data obtained from the radium subjects. These bands cover the spans from 275 to 375, 525 to 675, 775 to 1275, and 1575 to 2575 keV. Several energy bands were used to determine whether the effect of internal absorption or distribution could be decreased by using a particular band.

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Presentation of K^{42} data

The form in which the data in this paper are presented was selected to emphasize the differences in detection efficiency for subjects of different body builds. The data are presented in one of two ways. In the first, the counting-rates (suitably corrected for decay and elimination) yielded by the patients in a series are averaged and then the percentage by which a subject's own rate exceeds or falls below the average is given. With the second form, the patient's corrected counting-rate was divided by the counting-rate observed when a bottle containing the exact quantity injected was counted while positioned on a tray exactly 40 cm below the crystal. The first type of analysis is used when the deviation from the average found with a crystal of one size is compared with that found with a crystal of different size in a different position. The second type of analysis is used to permit an intercomparison between the data from two groups of patients observed with the same crystal, even though the patients in the two series received different quantities of K^{42}.

Inherent uncertainty when measuring alkali metals

The tilting-chair technique, the 1.75-m arc, and the 3-in×5-in crystal at the small of the back

Table I presents the data obtained from two groups of six patients, listed separately since they received different amounts of K^{42}. The patients in each group are listed in the order of increasing weights. Each patient's weight, height, and age are given. In addition, his average weight per inch of height is given to see if deviations from the average can be correlated with height, weight, or a combination of both.

Each patient's gamma-ray spectrum was measured in human spectrometer No. 2 with the 8-in×4-in NaI(Tl) crystal No. 2 and the 1.75-m-arc technique. He was measured first in the supine and then in the prone position. The patient then moved to human spectrometer No. 1, where his gamma-ray spectrum was measured with the 8-in×4-in NaI(Tl) crystal No. 1 and the tilting-chair technique. After each patient had been measured with both of the above techniques, he was remeasured in the tilting chair. The patients in the first group were also measured with a 3-in×5-in NaI(Tl) crystal at the small of the back during the second series of tilting-chair measurements. The pulses from each of the three crystals were analysed with the same 256-channel pulse-height analyser.

The photopeak data from the tilting chair will be examined first. Within each group (Table I), the counting-rate from the bottle of K^{42} is given in the first line, the average counting-rate from the six patients is given in the second, and the ratio of the counting-rate from the bottle to that of the patient average is given in the third. The agreement between the ratios of the two groups demonstrates that the detection efficiency of the tilting-chair technique was the same for both series of measurements. The percentage deviation of each patient's own counting-rate from the average is given next.

Within limits, the percentage deviation depends on the patient's weight; thus the four patients who weighed between 130 and 140 lb counted from 0.5 to 5.2% above the average, the five patients who weighed between 150 and 160 lb counted within 2% of the average, and the three patients who weighed between 180 and 200 lb counted from 3.5 to 4.5% below the average.

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TABLE I

PERCENTAGE VARIATIONS OBSERVED IN K^{42} MEASUREMENTS MADE WITH TILTING CHAIR, 1.75-m ARC AND CRYSTAL AT THE SMALL OF THE BACK

Subject	Weight (lb)	Height (in)	lb/in	Age (yr)	Tilting chair		3-in×5-in crystal at small of back		Average of front and back on 1.75-m arc		Ratio counts/min tilting chair / counts/min 1.75-m arc		Ratio of back to front on 1.75-m arc	
					Compton	Photopeak	Compton	Photopeak	Compton	Photopeak	Compton	Photopeak	Compton	Photopeak
Counts/min K^{42} in 405 g H_2O at 40 cm					46 930	72 000								
Average counts/min from six patients					34 507	41 561	13 051	11 029	2 465	3 519				
Ratio (Counts/min K^{42})/(Counts/min patients)					1.360	1.732								
					% dev.	% dev.								
5	137	65.5	2.10	38	— 2.170	+ 0.510	+ 5.40	+ 7.5	— 1.95	+ 1.00	13.61	11.44	1.04	1.02
6	138	65	2.12	64	+ 1.990	+ 3.030	+ 9.70	+12.2	+ 2.56	+ 2.80	13.83	11.71	1.02	1.04
11	152	66	2.30	62	+ 2.090	+ 1.700	— 1.15	— 1.4	+ 0.89	+ 1.76	13.92	11.49	1.04	1.04
13	155.20	63	2.46	73	— 1.350	— 1.830	+ 3.25	+ 3.7	— 1.20	— 1.70	13.85	11.67	1.05	1.05
14	158	64.5	2.46	70	+ 1.370	+ 0.929	— 4.81	— 7.2	0.00	+ 0.28	13.87	11.66	1.04	1.02
20	199	72	2.76	42	— 1.930	— 4.340	—12.40	—14.9	— 0.24	— 3.60	13.52	11.53	1.04	1.05
								Average			13.77	11.58		
Counts/min K^{42} in 405 g H_2O at 40 cm					14 093	67 800								
Average counts/min from six patients					31 748	39 171			2 333	3 482				
Ratio (Counts/min K^{42})/(Counts/min patients)					1.389	1.731								
3	130	66	1.97	31	— 0.520	+ 5.200			+ 0.38	+ 2.80	13.18	11.11	1.00	1.01
7	140	72	1.94	52	+ 0.600	+ 2.520			— 0.91	+ 2.50	13.47	10.99	1.01	1.02
12	152	68	2.24	49	+ 0.200	— 1.170			+ 2.30	+ 2.20	13.02	10.64	1.02	1.04
15	158	73.2	2.16	34	— 0.500	+ 0.870			— 1.80	+ 0.17	13.47	11.07	1.01	1.01
17	180	71.5	2.52	44	— 0.900	— 3.500			+ 1.90	— 1.52	12.93	10.77	1.04	1.04
18	180	72.2	2.49	42	+ 1.110	— 3.920			— 1.70	— 6.20	13.69	11.26	1.02	1.06
								Average			13.30	10.97		

Although there is no correlation between the patient's height or weight and his counting rate in the Compton-energy band (775—1275 keV), it is significant that there is considerably less deviation from the average in the Compton-energy band than in the photopeak band. Greater accuracy will be achieved when measuring a patient's normal K content if the counts from both energy bands are used, not only because of the larger number of counts and thus the better statistical average, but also because of the smaller dependence on body build. Unfortunately, only those counts that fall under the photopeak can be used when measuring the small amounts of any other isotope in the body if the energy of the gamma ray is less than that of normal K^{40} (1.46 MeV). Thus, the deviations found for the K photopeak are more representative of the accuracy that can be attained in practice than are those for the Compton band.

The data obtained with the 1.75-m-arc technique will be discussed next. The subject's anterior and posterior counting-rates were averaged and the percentage deviation of his average value from the average of the total group of patients was listed. In general, these deviations follow the same trend as those obtained with the tilting chair. Except for subject 12, the subjects counted about the same amount above or below the average with both techniques. Also, the over-all spread of values is as wide (+2.8% to —6% on the 1.75-m arc, as compared with +5.2% to —4.3% with the tilting chair). This correlation indicates that the variations in counting-rates observed with the tilting chair are due mainly to differences in internal absorption in the human body and not to differences in height or musculature.

On the 1.75-m arc, the subject's posterior counting-rate is always higher than hsi anterior counting-rate. (Last two columns of Table I.)

Because of its lack of sensitivity, the 1.75-m-arc technique would be used only if a subject contained a relatively very large quantity of activity or if the activity was concentrated in some linited volume of the body. The tilting chair provided a counting-rate about 11 times as high as that of the arc.

The data obtained with the 3-in × 5-in NaI(Tl) crystal located at the small of the back are given in Table I. The smaller subjects counted as much as 12% above the average, while the heaviest subject counted 15% below the average. The counting-rate per microcurie in the body varies greatly between subjects of the same height and weight. A 5% difference is noted between subjects 5 and 6 and a 10% difference among subjects 11, 13 and 14. Thus, this technique cannot be used to measure a subject's body content of natural K unless the subject is given a calibrating tracer. Additional data given in a later section will further support this conclusion.

Reproducibility of tilting-chair measurements

The data obtained from a third group of six K^{42} patients can be used to demonstrate the reproducibility of measurements made with the tilting-chair technique. Each patient, in turn, was seated in the tilting chair and measured first with the 8-in × 4-in crystal and then with the 9-in × 4-in crystal. The patient did not change position between these two measurements. After all patients had been measured once, each one again entered the room, was repositioned and remeasured with the 8-in × 4-in crystal only. The following day they were seated in the tilting chair and measured with both crystals. Since the patients did not change position between the measurement with the 8-in × 4-in crystal and the corresponding one with the 9-in × 4-in

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crystal, any changes in counting-rates caused by postural changes should be reflected in both measurements.

The data are given in Table II. The counting-rate from each subject was corrected for decay of K^{42} but not for the amount excreted. The first line gives the average counting-rate for each series of measurements and the second gives the percentage by which each patient's rate exceeded or fell below this average. Since the data have not been corrected for excretion, the individual percentage deviations from the mean do not necessarily reflect variations due to anatomical differences only.

On the average, the counting-rate in the photopeak with the 8-in × 4-in crystal was 1.3% lower during both the second and third series of measurements than during the first set. The counting-rate in the Compton band was 1.6% lower during the second series and 0.2% higher during the third series. In excellent agreement with these values, the average counting-rate with the 9-in × 4-in crystal was 1% lower in the Compton band and 0.8% lower in the photopeak for the third series of measurements than for the first series.

The reproducibility is even more remarkable if the data on an individual subject are considered, since they include individual variations in excretion. Subject 30, who showed the largest variation of all, gave a counting-rate 0.7% less than the average of the first series of measurements, 1.3% above the average of the second series, and 0.9% above the average of the third set. Thus, his counting-rate fell within ±1% of the same average each time. The counting-rates of the rest fell within ±0.5%.

A comparison of the data taken on the same subject with the 9-in × 4-in crystal with those taken with the 8-in × 4-in crystal demonstrates that the reproducibility is independent of crystal size. For example, subject 29 gave a counting-rate that was 1.0% higher in the Compton band and 6.2% lower in the photopeak than the average for the group, when measured with the 8-in × 4-in crystal. This same subject yielded a counting-rate which was 1.2% higher in the Compton band and 5.8% less in the photopeak than the average counting-rate for the group when measured with the 9-in × 4-in NaI(Tl) crystal. This agreement between the data taken with the two crystals demonstrates that the fact that subject 30 yields a counting-rate below average in the photopeak and above average in the Compton band is real and due to some anatomical difference between him and the others.

3-in × 5-in NaI(Tl) CRYSTAL UNDER THE SEAT

The six patients in the group discussed above were also measured with the 3-in × 5-in crystal mounted under the seat of the tilting chair. These data are also given in Table II to afford a direct comparison between the tilting-chair technique and this technique. Three patients (30, 19 and 4) gave counting-rates which were from 0 to 3% above the average with the tilting-chair technique. These same three subjects gave counting-rates which were 10% above, 9% below, and 12.5% above the average counting-rate for the group measured with the 3-in × 5-in crystal under the seat. Since these variations are due to anatomical differences between the subjects and not to changes in the position with respect to the crystal, it is evident that this is not the most practical way to measure the subject's radioactive content.

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TABLE II

REPRODUCIBILITY OF TILTING-CHAIR K^{42} MEASUREMENTS WITH TWO CRYSTALS OF DIFFERENT SIZES

Subject	Weight (lb)	Height (in)	Age (yr)	8-in × 4-in crystal over tilting chair						3-in × 5-in crystal under chair	
				1st measurement Wednesday 1-4 p. m.		2nd measurement Wednesday 4-5 p. m.		3rd measurement Thursday 10-12 a. m.		Measurement Wednesday 1-4 p. m.	
				Compton	Photopeak	Compton	Photopeak	Compton	Photopeak	Compton	Photopeak
Average counts/min % difference from first measurement				38 378	46 482	37 755 — 1.6	45 903 — 1.3	38 465 + 0.2	45 946 — 1.3	11 106	9 463
29	224¼	66¾	65	+ 1.0	— 6.2	+ 0.8	— 7.1	— 0.3	— 7.3	— 6.2	— 7.3
16	178	67¾	65	— 3.3	— 4.3	— 3.0	— 5.5	— 3.7	— 5.4	— 2.7	— 3.7
30	136	66½	43	— 5.6	— 0.7	— 4.5	+ 1.3	— 4.2	+ 0.9	+ 7.8	+ 9.8
19	184½	66½	59	+ 3.1	+ 1.1	+ 3.7	+ 1.5	+ 2.7	+ 0.9	— 8.6	— 8.8
4	137½	65¼	52	— 2.5	+ 2.7	— 1.5	+ 3.7	— 2.9	+ 2.8	+11.3	+12.5
31	179	69¾	41	+ 7.3	+ 7.4	+ 7.9	+ 7.2	+ 8.3	+ 8.2	— 0.7	— 2.4
				9-in × 4-in crystal over tilting chair							
				1st measurement Wednesday 1-4 p. m.				3rd measurement Thursday 10-12 a. m.			
Average counts/min % difference from first measurement				49 419	69 675			48 915 — 1.0	69 128 — 0.8		
29				+ 1.2	— 5.8			— 0.8	— 7.3		
16				— 2.3	— 4.3			— 3.6	— 4.8		
30				— 5.8	+ 0.6			— 3.6	+ 1.2		
19				+ 3.1	+ 1.4			+ 3.6	+ 1.7		
4				— 2.2	+ 2.6			— 1.8	+ 3.0		
31				+ 6.1	+ 6.7			+ 6.2	+ 6.1		

Multiple-crystal array

Crystals above supine or prone subjects

Measurements were made on six patients in the supine and prone positions to obtain experimental data for use in evaluating and designing multiple-crystal arrays. The patient was first placed in a supine position on an air mattress on a bed. The 9-in × 4-in crystal was positioned over the mid-line of the subject with the crystal face 30 cm above the surface of the bed. The subject's gamma-ray spectrum was measured with the crystal over the subject's mid-line at seven different equally-spaced positions along the length of the subject. The subject was positioned so that the point half way from the top of the subject's head to his ankle bone was directly under the centre position of the crystal. The same crystal positions were used for all subjects regardless of their height. The crystal was then raised so the crystal face was 40 cm from the surface of the bed and the measurements repeated. The patient then turned over to the prone position and the fourteen measurements were repeated.

Data presentation

Since the different groups of subjects received different amounts of K^{42}, the data were analysed as follows. The same volume of K^{42} as had been administered to each of the patients in a group was diluted into 405 g of distilled H_2O. This bottle of K^{42} was counted while located exactly 40 cm below the crystal. The counting-rates from both the bottle and the human were corrected for radioactive decay and the human data were corrected for the amount excreted. The human counting-rates, in two energy bands, were then divided by those observed in the same two energy bands from the bottle. These ratios have been designated "relative counting-rates".

The appropriate factors to convert the "relative counting-rates" into "counts per minute per gram of normal K in the body" were determined by counting, in exactly the same position and under the same scattering conditions as the K^{42}, a bottle that contained a known amount of KOH. These factors were 0.68 for the Compton ratio and 1.26 for the photopeak ratio. The relative rates are given in the tables, since the results are not restricted to K but are typical of those that would be observed when other alkali metals, which go to soft tissues, are given to the human.

Counting-rate at different positions

These ratios obtained with the crystal 30 cm above the bed are given in Table III, and the ratios with the crystal 40 cm above the bed are given in Table IV.

The photopeak ratios (subject/bottle) for subject 9 were plotted (Fig. 4). Subject 9 gave a counting-rate about 15% higher when the crystal was positioned over the back than when it was over the chest (crystal position 2). The same effect was noted when the crystal was positioned 40 cm above the bed. The counting-rate from the posterior and the anterior were about the same when over the centre position. The anterior reading over the thighs is about 6% higher than the corresponding posterior measurements. The anterior and posterior counting-rates over the shins (position 7) are about equal, but only about a quarter of that at position 3.

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TABLE III

RELATIVE K^{42} COUNTING-RATES WITH A 9-in × 4-in CRYSTAL LOCATED AT DIFFERENT POSITIONS 30 cm ABOVE THE BED

The subject is supine for the anterior measurement and prone for the posterior measurement

Subject	Energy band	Crystal position	1	2	3	4	5	6	7	Tilting chair / Bottle
No. 4 137½ lb 65¼ in 2.11 lb/in	Compton	anterior	0.479	0.864	1.090	1.040	0.804	0.492	0.287	0.714
		posterior	0.491	0.938	1.110	1.095	0.779	0.498	0.288	
	Photopeak	anterior	0.361	0.748	0.911	0.869	0.682	0.414	0.241	0.609
		posterior	0.373	0.789	0.917	0.882	0.656	0.431	0.243	
No. 9 145½ lb 67 in 2.17 lb/in	Compton	anterior	0.494	0.909	1.170	1.080	0.839	0.507	0.297	0.736
		posterior	0.529	1.020	1.170	1.080	0.795	0.504	0.299	
	Photopeak	anterior	0.372	0.713	0.893	0.838	0.683	0.411	0.242	0.598
		posterior	0.402	0.828	0.933	0.844	0.646	0.429	0.255	
No. 9	Compton	anterior	0.538	0.935	1.150	0.998	0.741	0.466	0.281	0.696
		posterior	0.543	1.026	1.150	1.021	0.712	0.471	0.281	
	Photopeak	anterior	0.428	0.759	0.908	0.795	0.608	0.385	0.235	0.570
		posterior	0.431	0.847	0.935	0.814	0.589	0.400	0.237	
No. 19 184½ lb 69¼ in 2.66 lb/in	Compton	anterior	0.591	0.969	1.030	0.891	0.648	0.392	0.226	0.753
		posterior	0.617	1.070	1.126	1.008	0.653	0.412	0.248	
	Photopeak	anterior	0.470	0.784	0.786	0.708	0.536	0.317	0.191	0.606
		posterior	0.490	0.866	0.884	0.785	0.539	0.355	0.206	
No. 29 200 lb 68½ in 2.92 lb/in	Compton	anterior	0.524	0.898	1.010	0.944	0.749	0.437	0.244	0.767
		posterior	0.469	0.922	1.060	1.001	0.756	0.483	0.290	
	Photopeak	anterior	0.400	0.680	0.740	0.714	0.580	0.342	0.196	0.588
		posterior	0.357	0.713	0.805	0.744	0.597	0.396	0.242	

TABLE IV

RELATIVE K^{42} COUNTING-RATES WITH A 9-in × 4-in CRYSTAL LOCATED AT DIFFERENT POSITIONS 40 cm ABOVE THE BED

The subject is supine for the anterior measurement and prone for the posterior measurement

Subject	Energy band	Crystal position	1	2	3	4	5	6	7	Tilting chair / Bottle
No. 4 137.5 lb 65.25 in 2.11 lb/in	Compton	anterior	0.371	0.608	0.721	0.702	0.561	0.384	0.239	0.714
		posterior	0.455	0.683	0.742	0.674	0.503	0.353	0.232	
	Photopeak	anterior	0.291	0.508	0.621	0.605	0.485	0.321	0.198	0.608
		posterior	0.366	0.586	0.627	0.568	0.431	0.299	0.193	
No. 9 145.5 lb 67 in 2.17 lb/in	Compton	anterior	0.373	0.623	0.771	0.730	0.578	0.391	0.236	0.736
		posterior	0.424	0.690	0.787	0.726	0.562	0.379	0.239	
	Photopeak	anterior	0.286	0.500	0.612	0.586	0.478	0.312	0.196	0.598
		posterior	0.322	0.565	0.644	0.593	0.463	0.317	0.195	
No. 19 184.25 lb 69.25 in 2.66 lb/in	Compton	anterior	0.441	0.678	0.735	0.654	0.494	0.321	0.204	0.754
		posterior	0.466	0.705	0.765	0.689	0.489	0.319	0.202	
	Photopeak	anterior	0.351	0.552	0.591	0.526	0.408	0.261	0.165	0.610
		posterior	0.368	0.582	0.619	0.550	0.403	0.272	0.167	
No. 21 200 lb 68.5 in 2.92 lb/in	Compton	anterior	0.388	0.605	0.693	0.656	0.523	0.341	0.204	0.767
		posterior	0.372	0.616	0.716	0.681	0.533	0.361	0.231	
	Photopeak	anterior	0.291	0.471	0.526	0.509	0.416	0.267	0.162	0.588
		posterior	0.283	0.488	0.561	0.529	0.430	0.291	0.186	
No. 24 254 lb 77.5 in 3.28 lb/in	Compton	anterior	0.443	0.637	0.693	0.625	0.516	0.357	0.231	0.836
		posterior	0.462	0.707	0.760	0.695	0.512	0.342	0.233	
	Photopeak	anterior	0.331	0.467	0.486	0.456	0.402	0.276	0.184	0.618
		posterior	0.352	0.525	0.548	0.502	0.393	0.279	0.193	

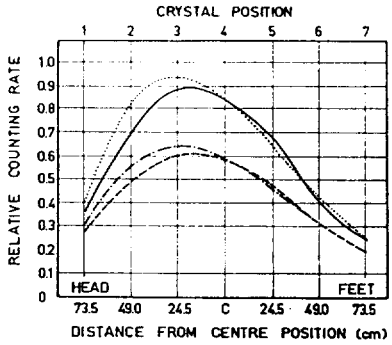

Fig. 4

Relative photopeak counting-rates observed at seven different crystal positions 30 cm and 40 cm above a patient containing K^{42}. The patient was counted supine (front) and prone (back). Unity on the ordinate scale denotes the counting-rate of the crystal when it is placed at 40 cm from a 405-cm³ bottle containing the same amount of K^{42} as the patient, duly corrected for decay and excretion (see text).

Subject 9:
30 cm: front ——— back . . . . . .
40 cm: front - - - - - - back —·—·—

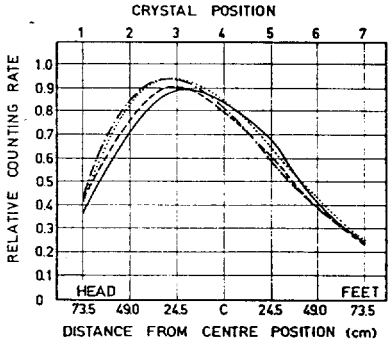

Fig. 5

Relative photopeak counting-rates observed on two different dates at the seven crystal positions 30 cm and 40 cm above the same K^{42}-containing patient. The patient was counted supine (front) and prone (back). Ordinate units as in Fig. 4.

Subject 9:
2 November 1960: front — — — back —·—·—
7 December 1960: front ——— back . . . . . .

The same subject was given K^{42} a month later and the measurements repeated (Fig. 5). Although the curves have about the same shape, it appears that the subject might have been positioned about 3 cm farther toward the foot of the bed when measured in the supine position.

The relative counting-rates, at the different positions for subjects 4 and 19, are shown in Fig. 6. The distribution of K along the length of the body is considerably different in these two subjects. Subject 4 gave almost the same counting-rate from the posterior as from the anterior position. In general shape, the curves of subject 4 match

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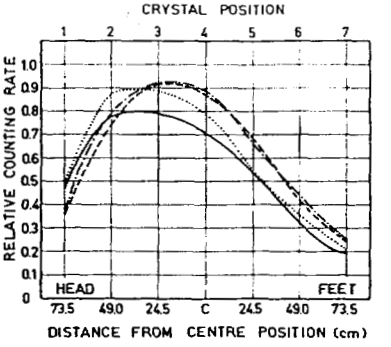

Fig. 6

Relative photopeak counting-rates observed at the seven crystal positions 30 cm and 40 cm above two patients containing equal amounts of K^{42}. The patients were counted while supine and prone. Ordinate units as in Fig. 4

Subject 4: front — — — back —·—·
Subject 19: front ——— back . . . . .

those of subject 9 (Fig. 4) except that subject 9 yielded a considerably higher counting-rate from the posterior than from the anterior position. The curves on subject 19, on the other hand, demonstrate not only the difference between front and back, but also a higher counting-rate at positions close to the head. Subject 19 was 5 cm taller than subject 9 and 10 cm taller than subject 4. This would have shifted subject 19's curve 2.5 and 5 cm respectively toward the head as compared with subjects 9 and 4.

Deviations between subjects with different crystal arrays

A particular crystal array will be chosen on the basis of three considerations: (1) cost; (2) sensitivity, i. e., the length of time necessary to achieve a stated number of counts; and (3) the lack of dependence of counting-rate on body build. To evaluate the different crystal arrays, the relative counting-rates of various combinations of crystals were added together. See Table V. The crystal positions selected are listed at the top of each column. The average relative counting-rate for the group of patients for each combination of crystals is given in the first three lines. The percentage by which each patient's relative counting-rate exceeded or fell below the average is given next. The second set of data on subject 9 was not used when computing averages, since this would have weighed the average in favour of his particular build.

Consider first the relative counting-rates in the photopeak. When an equal number of crystals were used both front and back, the first two subjects gave counting-rates 4 to 5% above the average, the third gave counting-rates about 2% less than the average and the last subject gave a counting-rate 7 to 8% less than the average. The percentage deviation is only slightly less if the relative counting-rate in the Compton band is considered. The surprising fact is that the same percentage variation from the average occurs with any arrangement of three or more crystals.

The relative counting-rates obtained with each subject in the tilting chair are given in the right-hand columns. These subjects yielded relative counting-rates with the tilting-chair technique which varied only 3% from the average but which varied

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TABLE V

RELATIVE K^{42} COUNTING-RATES AND RESULTING DEVIATIONS WITH VARIOUS NUMBERS OF CRYSTALS AT DIFFERENT POSITIONS 30 cm ABOVE THE BED

Subject	Crystals at positions	1—2—3—4—5—6—7		1—3—5—7		2—4—6		2—3—4		Tilting chair	
		Compton	Photopeak	Compton	Photopeak	Compton	Photopeak	Compton	Photopeak	Compton	Photopeak
		Relative counting-rate									
	average anterior	4.977	3.954	2.620	2.071	2.356	1.885	2.974	2.347	0.735	0.599
	average posterior	5.178	4.152	2.670	2.136	2.508	2.015	3.150	2.522		
	average both	10.156	8.107	5.290	4.207	4.864	3.900	6.124	4.869		
		Percentage deviations from the average									
No. 4	anterior	+ 1.8	+ 6.9	+ 1.5	+ 6.0	+ 1.7	+ 7.5	+ 0.7	+ 7.7	— 2.9	+ 1.5
	posterior	+ 0.4	+ 3.4	0.0	+ 2.5	+ 0.9	+ 4.3	— 0.2	+ 2.6		
	both	+ 1.0	+ 5.1	+ 0.8	+ 4.2	+ 1.3	+ 6.0	+ 0.2	+ 5.1		
No. 9	anterior	+ 6.5	+ 5.0	+ 6.9	+ 5.8	+ 6.0	+ 4.1	+ 6.2	+ 4.1	— 1.4	— 0.7
	posterior	+ 4.3	+ 4.5	+ 4.5	+ 4.7	+ 3.8	+ 4.3	+ 3.8	+ 3.3		
	both	+ 5.2	+ 4.7	+ 5.7	+ 5.2	+ 4.9	+ 4.2	+ 5.0	+ 3.7		
No. 9	anterior	+ 2.5	+ 3.7	+ 3.4	+ 5.2	+ 1.8	+ 2.9	+ 3.7	+ 4.9	— 3.7	— 3.7
	posterior	+ 0.5	+ 2.4	+ 0.6	+ 2.6	+ 0.4	+ 2.3	+ 1.5	+ 2.9		
	both	+ 1.4	+ 3.0	+ 2.0	+ 3.9	+ 1.1	+ 2.6	+ 2.6	+ 3.9		
No. 19	anterior	— 4.6	— 4.1	— 5.2	— 4.3	— 4.4	— 4.0	— 2.8	— 2.5	+ 2.5	+ 1.2
	posterior	— 0.9	— 0.7	— 1.0	— 0.8	— 0.7	— 0.4	+ 1.7	— 0.5		
	both	— 2.7	— 2.3	— 2.9	— 2.5	— 2.5	— 2.2	— 0.5	— 1.2		
No. 21	anterior	— 3.4	— 7.7	— 3.6	— 7.5	— 3.3	— 7.9	— 4.1	— 8.9	+ 2.0	— 2.2
	posterior	— 3.9	— 7.2	— 3.6	— 6.3	— 5.1	— 8.1	— 5.3	— 6.3		
	both	— 3.6	— 7.5	— 3.6	— 6.9	— 3.7	— 8.0	— 4.9	— 7.6		
Expected counts/min from normal subject with crystals anterior and posterior (120 g K assumed)		830	1 225	430	620	400	590	500	736	60	90

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from +5% to —7% from the various crystal arrays. The second measurement on subject 9 gave a value about 3% lower than the first measurement, both with the tilting chair and with the multiple-crystal array. This agreement between the tilting chair and the multiple-crystal array proves that the change is real and due to some anatomical difference. It is significant that this subject had been given medication to reduce his potassium content during the month between the two measurements.

The counting-rates that would be observed from the normal K content of the body with these crystal arrays is given at the bottom of the table. Although high sensitivity is realized, a large uncertainty would have to be attributed to all measurements, unless each subject is given a calibrating tracer.

The data obtained with the crystals 40 cm above the bed were analysed in the same manner. The data from five subjects are given in Table VI. The relative counting-rates exhibit the same spread as observed with the crystal 30 cm above the bed; the subjects simply yield a counting-rate 71% of that obtained with the same number of crystals located 30 cm above the bed. The fact that the counting-rate obtained at 40 cm from the bed is simply 71% of that observed at 30 cm demonstrates that staggering the heights of the various crystals cannot eliminate the deviation in counting-rates due to the anatomical difference between subjects. Thus, if multiple-crystal arrays are used, the crystals should be located as close to the bed as possible to obtain the highest possible counting-rate, but far enough away to accommodate the largest subject to be studied.

Crystals above and below a supine patient

The data presented above could not be used to evaluate an array of crystals above and below the patient. The gamma-ray spectra obtained with the crystals above the prone subject are not the same as the spectra that would be observed with crystals beneath the supine subject. Thus, the gamma-ray spectra of ten patients were obtained with the following physical arrangement.

The metal bed was replaced with a transparent sheet of lucite, 0.75 in thick, so the patient's position could be viewed from below. The patient was placed in a supine position directly on the lucite to fix the position of his posterior surfaces with respect to the crystals under the bed. His gamma-ray spectra were then obtained with the face of the crystal 36 and/or 30 cm above the bed and 20 and/or 10 cm below the bed at each of the seven crystal positions discussed above.

The data, tabulated as relative counting-rates at each crystal position, are given in Table VII for six subjects when the crystal face was 30 cm above and 10 cm below the bed. The relative counting-rates which would be obtained if various combinations of crystals were used simultaneously (Table VIII) were determined by adding the appropriate rates. The average relative counting-rates of the group of subjects with the crystal array 30 cm above and 10 cm below are given in the first two lines. The percentage by which each patient's own relative counting-rate exceeds or falls below this average is then given. The percentage deviation is considerably less when any array of crystals is used above the bed than when the same array is used below the bed. Thus, greater uncertainty will exist if crystals are used both above and below rather than just above. Again, the percentage deviation does not vary greatly among the different arrays of crystals except for the array of two crystals over the chest and abdomen.

The percentage deviations observed with the tilting chair are given in the last two columns. Except for patient No. 1, the deviations observed with the tilting

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TABLE VI

RELATIVE K^{42} COUNTING-RATES AND RESULTING DEVIATIONS WITH VARIOUS NUMBERS OF CRYSTALS AT DIFFERENT POSITIONS 40 cm ABOVE THE BED

Subject	Crystals at positions	1—2—3—4—5—6—7		1—3—5—7		2—4—6		2—3—4		Tilting chair	
		Compton	Photopeak	Compton	Photopeak	Compton	Photopeak	Compton	Photopeak	Compton	Photopeak
		Re ative counting-rate									
	average anterior	3.545	2.820	1.883	1.497	1.662	1.324	2.026	1.603	0.750	0.598
	average posterior	3.661	2.936	1.937	1.549	1.724	1.389	2.127	1.697		
	average both	7.206	5.756	3.820	3.046	3.386	2.713	4.153	3.301		
		Percentage deviations from the average									
No. 4	anterior	+ 1.2	+ 9.8	+ 0.5	+ 6.9	+ 1.9	+ 8.3	+ 0.3	+ 8.2	— 4.8	+ 1.5
	posterior	— 0.5	+ 4.5	— 0.3	+ 4.4	— 0.8	+ 4.6	— 1.3	+ 5.7		
	both	+ 0.3	+ 5.9	+ 0.1	+ 5.6	+ 0.5	+ 6.4	— 0.6	+ 6.5		
No. 9	anterior	+ 4.5	+ 7.0	+ 4.0	+ 5.0	+ 4.9	+ 5.6	+ 4.8	+ 5.9	— 3.3	— 0.7
	posterior	+ 4.0	+ 5.5	+ 3.9	+ 4.8	+ 4.1	+ 6.2	+ 3.6	+ 6.2		
	both	+ 4.2	+ 5.4	+ 3.9	+ 4.9	+ 4.3	+ 5.9	+ 4.2	+ 6.0		
No. 19	anterior	— 0.5	+ 1.6	— 0.5	+ 1.2	— 0.6	+ 1.1	+ 2.0	+ 4.1	+ 0.4	+ 1.3
	posterior	— 0.7	+ 0.8	— 0.8	+ 0.5	+ 0.6	+ 1.1	+ 1.5	+ 3.2		
	both	— 0.6	+ 1.0	— 0.6	+ 0.9	— 0.6	+ 1.1	+ 1.8	+ 3.6		
No. 21	anterior	— 3.8	— 8.2	— 4.0	— 6.8	— 3.6	— 5.8	— 3.6	— 5.8	0.0	— 2.0
	posterior	— 4.1	— 5.8	— 4.4	— 5.8	— 3.8	— 5.8	— 5.4	— 7.0		
	both	— 4.0	— 6.1	— 4.2	— 6.3	— 3.7	— 5.8	— 4.5	— 6.5		
No. 24	anterior	—1.2	—10.0	0.0	— 6.3	— 2.6	— 9.4	— 3.6	—12.0	+ 7.5	— 0.2
	posterior	+1.4	— 5.0	+ 1.6	— 4.1	+ 1.2	— 6.0	+ 1.6	— 7.2		
	both	+0.1	— 6.4	+ 0.8	— 5.2	— 0.7	— 7.6	— 0.9	— 9.6		
Expected counts/min from normal subject with crystals anterior and posterior (120 g K assumed)		590	870	310	460	280	410	340	500	61	100

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TABLE VII

RELATIVE K^{42} COUNTING-RATE WITH A 9-in × 4-in CRYSTAL LOCATED AT DIFFERENT LOCATIONS 30 cm ABOVE AND 10 cm BELOW THE LUCITE BED

Subjects are in a supine position

Subject	Energy band	Crystal position	1	2	3	4	5	6	7	Tilting chair / Bottle
No. 1 111 lb 67.7 in	Compton	30 cm above	0.396	0.731	1.027	1.015	0.727	0.426	0.280	0.651
		10 cm below	0.598	0.922	1.100	1.080	0.814	0.510	0.300	
	Photopeak	30 cm above	0.316	0.614	0.847	0.840	0.607	0.352	0.200	0.555
		10 cm below	0.447	0.709	0.820	0.797	0.614	0.386	0.231	
No. 2 128.2 lb 66.5 in	Compton	30 cm above	0.508	0.845	1.030	0.957	0.700	0.418	0.243	0.7226
		10 cm below	0.484	0.939	1.084	1.083	0.837	0.533	0.326	
	Photopeak	30 cm above	0.418	0.699	0.839	0.795	0.590	0.352	0.202	0.618
		10 cm below	0.351	0.712	0.801	0.813	0.645	0.418	0.254	
No. 4 136.1 lb 65 in	Compton	30 cm above	0.413	0.766	0.991	0.956	0.715	0.428	0.251	0.688
		10 cm below	0.430	0.919	1.120	1.096	0.876	0.557	0.325	
	Photopeak	30 cm above	0.326	0.632	0.794	0.783	0.601	0.358	0.209	0.582
		10 cm below	0.302	0.691	0.828	0.809	0.663	0.434	0.249	
No. 8 142 lb 63 in	Compton	30 cm above	0.417	0.805	1.064	1.018	0.763	0.448	0.250	0.705
		10 cm below	0.421	0.915	1.130	1.088	0.858	0.535	0.302	
	Photopeak	30 cm above	0.319	0.651	0.851	0.820	0.625	0.363	0.203	0.585
		10 cm below	0.289	0.683	0.828	0.795	0.643	0.411	0.226	
No. 10 152 lb 69.1 in	Compton	30 cm above	0.366	0.743	1.007	0.956	0.717	0.438	0.260	0.727
		10 cm below	0.378	0.759	0.930	0.917	0.687	0.444	0.274	
	Photopeak	30 cm above	0.281	0.587	0.777	0.745	0.569	0.350	0.200	0.591
		10 cm below	0.263	0.555	0.673	0.659	0.499	0.331	0.209	
No. 23 210.1 lb 73 in	Compton	30 cm above	0.503	0.823	0.947	0.901	0.688	0.388	0.226	0.771
		10 cm below	0.514	0.873	0.921	0.883	0.680	0.413	0.273	
	Photopeak	30 cm above	0.389	0.640	0.705	0.687	0.538	0.301	0.179	0.603
		10 cm below	0.358	0.624	0.643	0.608	0.486	0.301	0.204	

TABLE VIII

RELATIVE K^{42} COUNTING-RATES AND RESULTING DEVIATIONS WITH VARIOUS NUMBERS OF CRYSTALS AT DIFFERENT POSITIONS 30 cm ABOVE AND 10 cm BELOW THE SUPINE SUBJECT

Subject	Crystals at positions	1—2—3—4—5—6—7		1—3—5—7		2—3—4—5		3—4		Tilting chair	
		Compton	Photopeak	Compton	Photopeak	Compton	Photopeak	Compton	Photopeak	Compton	Photopeak
	average 30 cm above	4.592	3.693	2.415	1.931	3.482	2.806	1.978	1.581	0.711	0.589
	average 10 cm below	5.021	3.711	2.610	1.921	3.752	2.766	2.072	1.512		
No. 1	30 cm above	+ 2.2	+ 2.2	+ 0.6	+ 2.0	+ 0.5	+ 3.6	+ 3.1	+ 6.8	— 8.4	— 5.8
	10 cm below	+ 6.0	+ 7.9	+ 7.7	+10.0	+ 4.4	+ 6.3	+ 5.2	+ 6.9		
No. 2	30 cm above	+ 2.4	+ 5.5	+ 2.7	+ 6.1	+ 1.4	+ 4.2	+ 0.5	+ 3.4	+ 1.6	+ 4.9
	10 cm below	+ 5.3	+ 7.6	+ 4.6	+ 6.8	+ 5.1	+ 7.4	+ 4.6	+ 6.8		
No. 4	30 cm above	— 1.6	+ 0.3	— 1.9	0.0	— 1.6	+ 0.1	— 1.6	— 0.3	— 3.2	— 1.2
	10 cm below	+ 6.0	+ 7.3	+ 5.4	+ 6.3	+ 6.9	+ 8.1	+ 6.9	+ 8.3		
No. 8	30 cm above	+ 3.8	+ 3.8	+ 3.3	+ 3.5	+ 4.8	+ 5.0	+ 5.3	+ 5.7	— 0.8	— 0.7
	10 cm below	+ 4.5	+ 4.4	+ 3.9	+ 3.4	+ 6.4	+ 6.6	+ 7.0	+ 7.3		
No. 10	30 cm above	— 2.3	— 5.0	— 2.7	— 5.4	— 1.7	— 4.6	— 0.8	— 3.7	+ 2.2	+ 0.3
	10 cm below	—12.6	—14.1	—13.1	—14.4	—12.2	—13.7	—10.9	—18.5		
No. 23	30 cm above	— 2.5	— 6.9	— 2.1	— 6.2	— 3.5	— 8.4	— 6.6	—12.0	+ 8.4	+ 2.4
	10 cm below	— 9.2	—13.1	— 8.5	—12.0	—10.5	—14.6	—12.9	—17.3		
Expected counts/min with crystals above or below supine normal subject containing 120 g K	Above	375	560	200	290	285	420	160	240	58	89
	Below	410	560	210	290	306	420	170	230		

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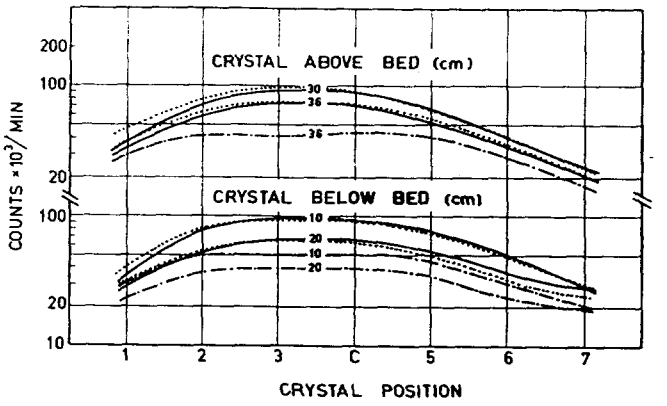

Fig. 7

Net counting-rates observed at the seven crystal positions at specified distance above and below three supine patients. Ordinates normalized to equal body contents of K^{42}

Subject 2 . . . . . Subject 4 ——— Subject 28 —·—·

chair are considerably less than those observed with the arrays of crystals. One fact is very significant. The counting-rate will vary greatly from subject to subject when crystals are placed a fixed distance fron the backs of subjects who contain the same amount of radioactivity. This is the same effect as that observed when a 3-in × 5-in crystal was mounted behind the tilting chair.

The data obtained with the crystals 36 cm above and 20 cm below the bed are given graphically in Fig. 7. Except for crystal positions 1 and 7, the two counting-rates differed by a fixed percentage. Thus, the percentage variation due to differences in the distribution within the body is not reduced by changing the crystal position from 30 cm to 36 cm above the bed or from 10 cm to 20 cm below it.

The data obtained on four patients who weighed over 300 lb are not given. The data obtained with patient No. 28 are given in Fig. 7. The average counting-rates observed from the heavy patients were about 60% of those observed from the thinner patients. Thus, much larger variations will occur if very heavy patients are measured.

Selection of crystal size

In order to determine experimentally the most economical utilization of sodium iodide crystals, a series of measurements were made on two subjects with crystals of various sizes. The two patients were first counted in the tilting chair with a 4-in × 4-in, a 9-in × 4-in, and an 11.5-in × 4-in NaI(Tl) crystal. They were then counted, in turn, in the supine position with each of the three crystals suspended 30 cm above the lucite bed, and with the 9-in × 4-in crystal 10 cm below the bed. Only the first six of the seven crystal positions shown in Fig. 3 were used with the 4-in × 4-in and the 9-in × 4-in crystals above the bed. All seven positions were used with the 11.5-in × 4-in crystal above the bed and with the 9-in × 4-in crystal beneath the bed.

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Because of the great interest in this topic, the actual net integrated counting-rates, corrected for excretion and radioactive decay, in the three energy bands used to measure the potassium and caesium content of normal humans are given in Tables IX to XI. The data obtained with both subjects with the 4-in × 4-in crystal are given in Table IX, those with the 9-in × 4-in crystal in Table X, and those with the 11.5-in × 4-in crystal in Table XI.

To determine whether the counting-rate increased linearly with crystal volume, the net counting-rate for the 9-in × 4-in and the 11.5-in × 4-in crystals were each divided by the counting-rate observed with the 4-in × 4-in crystal. The ratios for each crystal position are given in Table XII. The 9-in × 4-in crystal has 5.06 times, and the 11.5-in × 4-in crystal 8.26 times, the volume of the 4-in × 4-in crystal. In the photopeak with the tilting-chair, the 9-in × 4-in crystal gave 5.63 times the counting-rate of the 4-in × 4-in crystal, and the 11.5-in × 4-in crystal gave 9.3 times the counting-rate of the 4-in × 4-in crystal. This gain in counting-rate with crystal size is even more significant when the shape of the total gamma-ray spectra are considered. The three net K^{42} spectra of this patient in the tilting chair were normalized to the same area under the photopeak: see Fig. 8, where it is clearly shown that the rela-

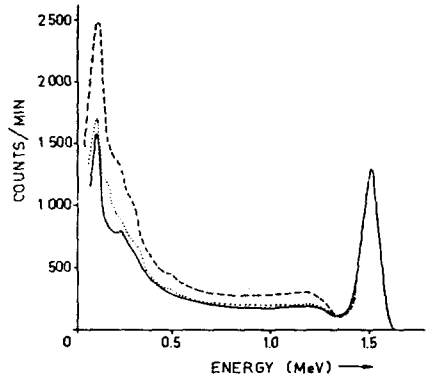

Fig. 8

Gamma-ray spectra obtained with three crystals over a subject in the tilting chair. The three K^{42} spectra were normalized to the same area in the photopeak to demonstrate the difference in counting-rates at low energies

4- in × 4-in crystal - - - - - - -
9- in × 4-in crystal . . . . . .
11.5-in × 4-in crystal ————

tive number of counts in the Compton band is considerably less with the larger crystals than with the 4-in × 4-in crystal. Thus the larger crystals are the obvious choice for the study of any isotope that emits a gamma ray whose energy falls below that of potassium.

In order to compare the counting-rate from a group of 4-in × 4-in crystals placed along the subject with that from a single large crystal over the tilting chair, the counts observed at each of the six locations 30 cm above the bed are summed (Tables IX, X, and XI). The six crystals, whose total volume is 1.19 times that of the 9-in × 4-in crystal, yielded a counting-rate 1.02 times that of the 9-in × 4-in crystal for patient No. 10 and 1.18 times that for patient No. 1. It is again obvious that a single large crystal used over the tilting chair gives more accurate and reproducible results

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TABLE IX

K^{42} COUNTING-RATE IN VARIOUS ENERGY BANDS WITH A 4-in×4-in NaI(Tl) CRYSTAL

Energy band (keV)	Crystal at positions	Crystal 30 cm above bed						Sum of 1—6	Crystal over tilting chair	K^{42} on tray at 40 cm from crystal
		1	2	3	4	5	6			
525—725	counts/min patient 10	2 833	5 450	7 750	7 447	5 404	3 461	32 345	5 138	5 580
	ratio patient 1/10	1.07	0.98	0.98	1.03	1.04	0.95	1.01	0.91	
	counts/min patient 1	3 035	5 342	7 577	7 709	5 635	3 357	32 655	4 677	
775—1275	counts/min patient 10	5 690	11 470	15 827	15 086	11 312	7 151	66 536	10 811	14 227
	ratio patient 1/10	1.12	1.01	1.02	1.07	1.05	1.02	1.04	0.93	
	counts/min patient 1	6 395	11 549	16 122	16 200	11 894	7 294	69 454	10 082	
1375—1625	counts/min patient 10	5 379	11 055	15 244	14 644	11 257	7 143	64 722	10 795	16 230
	ratio patient 1/10	1.16	1.05	1.03	1.11	1.09	1.03	1.08	0.98	
	counts/min patient 1	6 231	11 656	16 203	16 284	12 232	7 338	69 944	10 575	

TABLE X

K^{42} COUNTING-RATE IN VARIOUS ENERGY BANDS WITH A 9-in×4-in NaI(Tl) CRYSTAL

Energy band (keV)	Crystal at positions	Crystal 30 cm above bed						Sum of 1—6	Crystal over tilting chair	K^{42} on tray at 40 cm from crystal
		1	2	3	4	5	6			
525—725	counts/min patient 10	10 455	21 754	29 807	28 000	20 832	12 373	123 221	21 279	27 000
	ratio patient 1/10	1.07	0.95	0.98	1.04	0.98	0.95	0.99	0.90	
	counts/min patient 1	11 145	20 557	29 389	29 353	20 322	11 734	122 500	19 150	
775—1275	counts/min patient 10	21 721	44 122	59 833	56 785	42 630	26 013	251 104	43 226	59 200
	ratio patient 1/10	1.08	0.99	1.02	1.06	1.01	0.97	1.02	0.93	
	counts/min patient 1	23 524	43 448	61 019	60 315	43 204	25 301	256 811	38 674	
1375—1625	counts/min patient 10	30 112	62 950	83 306	79 862	61 044	37 490	354 764	63 378	107 250
	ratio patient 1/10	1.12	1.04	1.09	1.13	1.07	1.01	1.08	0.97	
	counts/min patient 1	33 884	65 818	90 874	90 080	65 097	37 713	383 466	59 500	

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TABLE XI

K^{42} COUNTING-RATE IN VARIOUS ENERGY BANDS WITH A 11.5-in × 4-in NaI(Tl) CRYSTAL

Energy band (keV)	Crystal at positions	Crystal 30 cm above bed							Sum of 1—6	Crystal over tilting chair	K^{42} on tray at 40 cm from crystal
		1	2	3	4	5	6	7			
525— 725	counts/min patient 10	18 085	33 696	43 002	40 791	28 870	17 060	9 802	181 504	31 160	37 000
	ratio patient 1/10	1.06	0.95	1.02	1.04	1.00	0.95	0.89	1.01	0.89	
	counts/min patient 1	19 142	32 037	43 878	42 345	28 936	16 198	8 729	182 536	27 630	
775—1275	counts/min patient 10	37 511	69 096	86 988	81 583	59 876	36 357	20 846	371 411	62 017	86 259
	ratio patient 1/10	1.07	0.97	1.04	1.06	1.03	0.96	0.92	1.06	0.94	
	counts/min patient 1	39 997	67 163	90 115	86 600	61 388	35 079	19 093	380 342	58 219	
1375—1625	counts/min patient 10	57 617	107 926	133 166	127 524	96 044	57 143	33 533	579 420	99 296	169 020
	ratio patient 1/10	1.11	1.04	1.13	1.13	1.06	0.99	0.92	1.09	0.99	
	counts/min patient 1	64 110	112 661	149 615	143 902	101 831	56 821	30 812	628 940	98 373	

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TABLE XII

RELATIVE K^{42} COUNTING-RATES OF THREE CRYSTALS AT EACH OF THE STANDARD CRYSTAL POSITIONS

Energy band (keV)	Crystal at positions	Crystal 30 cm above bed						Sum of 1—6	Crystal over tilting chair
		1	2	3	4	5	6		
525—725	Counts/min $\frac{9\times4}{4\times4}$	3.67	3.85	3.88	3.81	3.61	3.50	3.75	3.95
	Counts/min $\frac{11.5\times4}{4\times4}$	6.30	6.00	5.79	5.49	5.14	4.83	5.59	5.91
775—1275	Counts/min $\frac{9\times4}{4\times4}$	3.68	3.76	3.78	3.72	3.63	3.47	3.70	3.84
	Counts/min $\frac{11.5\times4}{4\times4}$	6.25	5.82	5.59	5.34	5.16	4.81	5.48	5.77
1375—1625	Counts/min $\frac{9\times4}{4\times4}$	5.44	5.65	5.61	5.53	5.32	5.14	5.48	5.63
	Counts/min $\frac{11.5\times4}{4\times4}$	10.30	9.67	9.23	8.84	8.32	7.74	8.99	9.30

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than does the same total volume of sodium iodide in the form of small crystals over the bed.

These data were also analysed to see if the variations in counting-rate as a function of body build could be eliminated by the use of crystals of appropriate size. The ratio of the counting-rate from patient 1 to that from patient 10 is given for each crystal position (Tables IX—XI). Although different ratios exist for different crystal positions, the ratio is about the same for all three crystals for any particular crystal position. For example, consider the ratio between the counting-rates in the photopeak at position 4. The ratio is 1.11 with the 4-in × 4-in crystal, 1.13 with the 9-in × 4-in crystal and 1.13 with the 11.5-in × 4-in crystal. This similarity is shown to exist for all crystal positions by the graphical display of the counting-rates in Fig. 9.

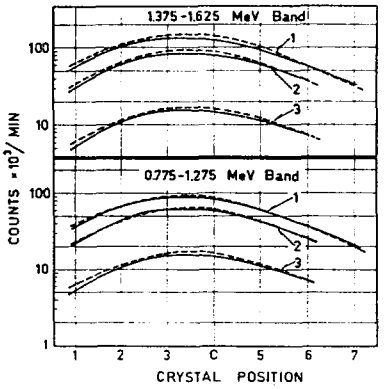

Fig. 9

Photopeak and "Compton" counting-rates from three different-sized crystals placed at seven positions 30 cm above two supine subjects containing K^{42}. Ordinates normalized to equal radioactive burden. Note similar relationship of counting-rates in subject 1 compared with that of subject 10, regardless of crystal size or energy band.

NaI (Tl) crystals:
1—11.5 in × 4 in
2— 9 in × 4 in
3— 4 in × 4 in
Subject 1 — — — Subject 10 ———

Analogously, with the tilting-chair technique the ratio of the counting-rate in the photopeak from patient 1 to that from patient 10 is 0.98 with the 4-in × 4-in crystal, 0.97 with the 9-in × 4-in crystal and 0.98 with the 11.5-in × 4-in crystal. This constancy of the ratio shows that the variation in counting-rate is due to the patient's musculature, etc., and cannot be eliminated by using a crystal of a particular size.

Uncertainty in normal potassium measurements with the tilting chair with an 8-in × 4-in crystal

For the benefit of the numerous investigators interested in the normal potassium content of humans, it will be recalled that a patient's body content, when given a trace of K^{42}, is calculated with the equation

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$$K\,(\text{grams}) = A \cdot \frac{B}{C} \cdot \frac{D}{E},$$

where, for a given energy band:

A is the patient's counting-rate observed; B/C is the mass (in g) of normal potassium in the standard divided by the counting-rate (counts/min); E is the net counting-rate observed from the K^{42} in the patient's body; D is the counting-rate observed when a quantity of K^{42} equal to that in the patient is counted at the same position and in the same scattering mass as those used in counting the normal potassium standard. The factor (D/E), hereafter called g*, is the reciprocal of the relative counting-rates used heretofore in this paper.

In what follows a normal patient's potassium content is calculated for two energy bands. A Compton-energy band from 0.775 to 1.275 MeV and a photopeak band from 1.375 to 1.625 MeV are used. Typical spectra are given in Fig. 10. The quantity

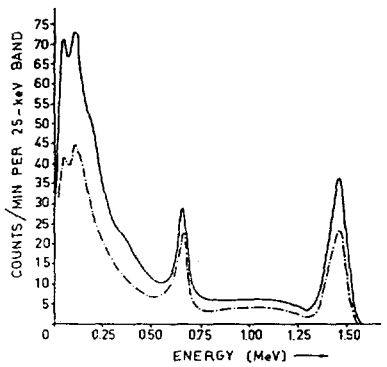

Fig. 10

Typical K^{40} and Cs^{137} gamma-ray spectra of two normal human beings on tilting chair. 11.5-in × 4-in NaI(Tl) crystal used.

calculated from the two bands should agree within the standard deviations arising from the statistics of counting. If the two values fall outside these limits, the subject's spectrum should be examined for the presence of another isotope.

In Table XIII are given the g-factors for both bands for all subjects and the average for the group is given at the bottom. The percentage by which each subject's g-factor exceeded or fell below the average is given in the column following each g-factor. The average of these two errors is given in the right-hand column. This average, of course, is the error that would have been committed if the average values of g had been taken in our computations.

Our findings show that when subjects weighing between 100 and 220 lb are measured an uncertainty of 2.5% could be given to any potassium measurement with 67% confidence and one of 3.5% could be given with 90% confidence if both energy bands are used. It should be kept in mind that a larger uncertainty will be present in measurements of other isotopes, since only those counts falling under

* The g-factor for patient 24 was not included in the average since the patient had curvature of the spine.

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the photopeak can be used; thus, an uncertainty of 4% could be given with 60% confidence to a potassium measurement based on the photopeak only.

In the past, any discussion of a human-body counter involved a discussion of the length of time that the patient had to be counted to obtain, say, 2% statistical accuracy. Obviously, there is little point in striving for high statistical accuracy in a measurement that contains a greater uncertainty arising from other causes.

TABLE XIII

GEOMETRICAL CONSTANT g CALCULATED FOR 28 SUBJECTS WITH THE 8-in × 4-in CRYSTAL OVER THE TILTING CHAIR

Patient	Weight	Height	lb/in	Compton band		Photopeak band		Average error (%)
				g_1	deviation from average (%)	g_2	deviation from average (%)	
Subjects weighing 100 to 299 lb								
No. 1	111	67.7	1.64	1.544	+10.5	1.835	+ 4.1	+ 7.3
No. 2	128.2	66.5	1.93	1.406	+ 0.6	1.677	— 4.9	— 2.2
No. 3	130	66	1.97	1.399	+ 0.1	1.673	— 5.1	— 2.5
No. 4	136.1	65	2.09	1.466	+ 4.9	1.744	— 1.1	+ 1.9
No. 5	137	65.5	2.10	1.405	+ 0.5	1.752	— 0.7	— 0.1
No. 6	138	65	2.12	1.348	— 3.6	1.709	— 3.1	— 3.4
No. 7	140	72	1.94	1.384	— 1.0	1.696	— 3.8	— 2.4
No. 8	142	63	2.25	1.417	+ 1.4	1.751	— 0.7	+ 0.4
No. 9	145.5	65.5	2.22	1.422	+ 1.7	1.779	+ 0.9	+ 1.3
No. 10	152	69.1	2.20	1.451	+ 3.8	1.802	+ 2.2	+ 3.0
No. 11	152	66	2.30	1.346	— 3.7	1.731	— 1.9	— 2.8
No. 12	152	68	3.24	1.389	— 0.7	1.759	— 0.3	— 0.5
No. 13	155.2	63	2.46	1.393	— 0.4	1.794	+ 1.7	+ 0.7
No. 14	158	64.5	2.46	1.356	— 3.0	1.744	— 1.1	— 2.1
No. 15	158	73.2	2.16	1.399	+ 0.1	1.723	— 2.3	— 1.1
No. 16	178	67.7	2.63	1.399	+ 0.1	1.830	+ 3.8	+ 2.0
No. 17	180	71.5	2.52	1.405	+ 0.5	1.801	+ 2.1	+ 1.3
No. 18	180	72.2	2.49	1.307	— 6.5	1.810	+ 2.6	— 2.0
No. 19	184.5	69.5	2.66	1.368	— 2.2	1.710	— 3.0	— 2.7
No. 20	199	72	2.76	1.401	+ 0.2	1.840	+ 4.4	+ 2.3
No. 21	200	65	3.08	1.411	+ 0.9	1.854	+ 5.1	+ 3.0
No. 22	206.5	69	3.00	1.401	+ 0.2	1.819	+ 3.2	+ 1.7
No. 23	210.1	73	2.88	1.330	— 4.9	1.726	— 2.1	— 3.5
No. 24 *	254	77.5	3.28	1.216	—13.7	1.693	— 5.7	— 9.37
		Average		1.398		1.763		
Subjects weighing over 300 lb								
No. 25	313	69	4.54	1.341	— 6.0	1.951	—12.3	— 9.1
No. 26	335	68	4.93	1.457	+ 2.2	2.385	+ 7.2	+ 4.7
No. 27	343.6	69	4.98	1.450	+ 1.7	2.277	+ 2.4	+ 2.1
No. 28	363	72	5.04	1.455	+ 1.0	2.283	+ 2.7	+ 1.9
		Average		1.426		2.224		

* Subject 24 was not included in average

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Inherent uncertainty when measuring alkaline earths

All of the data presented thus far were obtained with the alkali metal K, which concentrates in soft tissue. Similar, or larger, inherent uncertainties are to be expected when the other alkali metals, such as Cs^{137} or Rb^{86}, which emit gamma rays of lower energy, are present.

These data cannot be used to evaluate the variations that will exist in measurements of alkaline earths, such as radium or calcium, which concentrate in the skeleton. First, the distribution of bone in the body is different from that of muscle, and second, alkaline earths are not taken up uniformly throughout the bone, but deposit selectively in the areas of bone growth. Thus, the total-body gamma-ray spectra of a group of patients who had received Ra^{226} intravenously, at the rate of 10 μc per week for from 9 to 36 weeks during 1931, were determined with various techniques.

These patients were measured on the 1.75-m arc, in the tilting chair, with the 3-in × 5-in crystal behind the back, and on the bed with a crystal placed at the seven standard positions both 30 cm above and 10 cm below the subject.

1.75-m-ARC TECHNIQUE

The measurements on the ten patients with the 1.75-m arc, the tilting chair, and the 3-in × 5-in crystal are summarized in Table XIV. The patients' code numbers are given on line 1, their heights on line 2, and their weights on line 3. The number of injections of radium each patient received is given on line 4. The subject's radium body contents as calculated from the 1.75-m-arc data are given on line 5 (when facing the crystal) and on line 6 (when facing away from the crystal). These values were arrived at by dividing the patient's counting-rate by the counting-rate observed when a sealed 1-μc radium source was buried in the centre of a pressed-wood phantom 14 cm thick and placed on the 1.75-m arc in the place of the patient.

Whether the patient counted higher from the front or the back and the percentage are stated on lines 7 and 8. Note that, although some subjects counted as much as 10% higher from the front than from the back, the opposite is true for others. This effect can only be due to differences in the distribution of either radium or bone within the subjects' bodies, and is definitely not due to movement of the hands, legs, etc., nor is it due to changes in the relative position of the patient with respect to the crystal. A nurse was present inside the iron room during all measurements to make sure that the subject did not move.

The front and back values found from the 1.75-m-arc data, given on lines 5 and 6, were accepted as the correct values. To afford a direct comparison between subjects, irrespective of their total body content, the counting-rates obtained with the other techniques were divided by this average value to give a calibration factor in counts per minute per μc of RaB and RaC (counts/min μc).

Some comments on these techniques are in order.

3-in × 5-in CRYSTAL BEHIND THE BACK

The calibration factors in counts/min μc obtained in the energy band from 25 keV to 1.55 MeV with the 3-in × 5-in crystal behind the back are given in line 9 and the percentage of the average for all patients in line 10. Although the nine subjects

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TABLE XIV

TABULATION OF DATA OBTAINED FROM RADIUM-BEARING PATIENTS WHEN MEASURED ON 1.75-m ARC, IN THE TILTING CHAIR, AND WITH A 3-in × 5-in CRYSTAL AT THE SMALL OF THE BACK

Code number of patients	03—121	03—114	03—101	03—111	03—110	03—112	03—115	03—125	03—135	03—139	Average
Height (in)	56.500	57	58	59	63	64	65	66	67	69	
Weight (lb)	100	111	116	108	153	140	152	134	140	134	
Number of injections in 1931	9	36	15	20	20	26	26	11	—	11	
μc Ra B + Ra C, 1.75-m arc, facing crystal	0.177	0.380	0.529	0.345	0.238	2.010	0.287	0.335	0.410	0.160	
μc Ra B + Ra C, 1.75-m arc, back to crystal	0.174	0.420	0.518	0.313	0.246	2.020	0.310	0.327	0.390	0.167	
Highest arc reading from	Front	Back	Front	Front	Back	Same	Back	Front	Front	Back	
% higher (see text)	1.700	10	2	10	5	0	8	2	5	4	
Counts/min μc, 3-in × 5-in crystal	20 400	44 600	20 400	16 000	21 200	22 600	27 200	15 400	—	10 800	22 070
% of average counts/min μc	92.400	202	92.400	72.500	96.100	102.400	123.200	70	—	48.900	
Counts/min μc, 8-in × 4-in crystal, tilting chair	44 000	44 300	45 700	43 700	40 500	38 700	37 300	39 400	42 200	43 000	40 800
% of average counts/min μc	108	108.500	112	107	98	95	91.400	96.500	104	105	

gave an average counting-rate of 22 000 counts/min μc, note that subject 03—114 yielded 44 600 counts/min μc, or 202% of the average value, whereas subject 03—139 yielded 10 800, or 49% of the average value. Thus an uncertainty of at least a factor of two could exist in any Ra determination based solely on measurements with a crystal at the back of a sitting patient.

Tilting-chair results

In order to simplify the table and the discussion, the number of counts obtained in four energy bands usually used to calculate body Ra have been added together. These bands, chosen to avoid Cs^{137} and K^{40} peaks, are 75 keV and 375 keV, between 525 keV and 657 keV, between 775 keV and 1.275 MeV, and between 1.675 MeV and 2.675 MeV. These individual totals, divided by their corresponding burdens as found with the 1.75-m arc, are given in line 11. The average of the ten totals is given in the right-hand column of line 11. Each subject's total is given as a percentage of the average value in line 12. Note the extreme variations, namely that subject No. 03—101 yields 112% as many counts per μc as the average and that subject No. 13—115 yields 91.4% as many counts per μc as the average. This is a definite improvement over the technique described immediately above.

Multiple-crystal array

Because of the striking variations in their counting-rates, and in order to learn something about the distribution of Ra throughout the length of their bodies, four patients were chosen for study with the 9-in × 4-in crystal at each of the seven positions 30 cm above the bed and 10 cm below it. The counting-rates in the 525—675-keV band of the spectrum from each patient were normalized to 1 μc by use of the radium content calculated with the 1.75-m arc and are plotted in Fig. 11. These curves demonstrate that the distribution of radium in one patient's body is completely different from that in another. A direct correlation can be observed

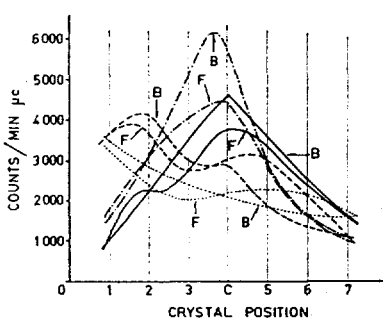

Fig. 11

Counting-rate in 525—675-keV band of 9-in × 4-in NaI(Tl) crystal used in conjunction with four patients containing a normalized burden of 1 μc Ra C. Patient supine on lucite table. Crystal placed at seven positions 30 cm above (front—F) and 10 cm below (back—B) top surface of lucite bed.

Subjects:

03—101 - - - - - 03—114 —.—.—
03—121 ——— 03—125 . . . . . .

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TABLE XV

PERCENTAGE DEVIATIONS IN COUNTING-RATES IN DIFFERENT ENERGY BANDS

Radium-bearing patient in supine position, normalized burden 1 μc Ra C

Subject	Crystals at positions	1—2—3—4—5—6—7			
	Energy bands (keV)	275—375	525—675	775—1275	1575—2575
	Average counts/min 30 cm above	62 725	40 973	35 775	17 932
	Average counts/min 10 cm below	63 511	40 870	37 908	18 593
No. 03—121 4 ft 8½ in 100 lb	Crystals 30 cm above	— 1.4	— 1.3	— 3.3	— 3.3
	Crystals 10 cm below	+ 1.8	+ 2.4	+ 1.9	+ 3.0
No. 03—114 4 ft 9 in 111 lb	Crystals 30 cm above	+ 5.6	+ 4.4	+ 6.5	+ 5.2
	Crystals 10 cm below	+15.8	+14.7	+15.7	+15.0
No. 03—101 4 ft 10 in 116 lb	Crystals 30 cm above	+ 5.1	+ 6.2	+ 6.7	+ 8.5
	Crystals 10 cm below	— 4.1	— 3.1	— 4.3	— 3.2
No. 03—125 5 ft 6 in 134 lb	Crystals 30 cm above	— 9.3	— 9.3	— 9.9	—10.4
	Crystals 10 cm below	—13.5	—14.0	—13.3	—14.8

between the counting-rates at position 3 and the results given in Table XIV for the 3-in × 5-in crystal. These curves also demonstrate that a large error will exist if a subject's body content of any alkaline earth is measured with a limited number of crystals placed along the supine subject. There is no reason to assume that the distribution of any other alkaline earth in the body will be more uniformly distributed, particularly if received in a single injection.

Using the data in Fig. 11 it is possible to calculate the uncertainties that would exist with other arrays of crystals. Thus, data obtained in the four energy bands mentioned earlier, as applied to an array of 7 crystals, are given in Table XV. The average counting-rate in each energy band for the four subjects is given first, followed by the percentage by which each subject's own rate exceeds (+) or falls below (—) each average. It is apparent that each patient's counting-rate deviates from the average by the same percentage, regardless of which energy band was used, and that, as with potassium, the variations observed with the crystals over the patient are less than those with the crystals under the patient.

Since the same variations existed regardless of the energy bands, the data for all bands are not given for the other crystal arrays; only the representative counting-rates observed in the band from 525 to 675 keV are shown in Table XVI. The variations observed with crystals at positions 1, 2, 3, 4, 5, 6 and 7 or at positions 1, 3, 5 and 7 agree with the variations observed with the tilting chair (last column). How-

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TABLE XVI

PER-CENT DEVIATIONS IN COUNTING-RATES WHICH RESULT WHEN DIFFERENT NUMBERS OF CRYSTALS ARE USED

Radium-bearing patient in supine position, normalized burden 1 μc Ra C

Subject	Crystals at positions	1—2—3—4—5—6—7	1—3—5—7	2—4—6	2—3—4	Tilting chair
	Energy bands (keV)	525—675	525—675	525—675	525—675	525—675
	Average counts/min 30 cm above	40 973	21 889	19 084	20 871	6 121
	Average counts/min 10 cm below	40 870	21 583	19 288	23 304	
No. 03—121 4 ft 8½ in 100 lb	Crystal 30 cm above	— 1.3	— 5.1	+ 3.2	— 2.0	+ 5.7
	Crystal 10 cm below	+ 2.4	— 0.8	+ 6.0	— 1.1	
No. 03—114 4 ft 9 in 111 lb	Crystal 30 cm above	+ 4.4	— 1.0	+10.5	+26.7	— 2.6
	Crystal 10 cm below	+14.7	+ 8.7	+21.4	+35.0	
No. 03—101 4 ft 10 in 116 lb	Crystal 30 cm above	+ 6.2	+ 8.2	+ 3.9	+ 1.6	+ 5.0
	Crystal 10 cm below	— 3.1	— 2.1	— 4.3	— 5.9	
No. 03—125 5 ft 6 in 134 lb	Crystal 30 cm above	— 9.3	— 2.0	—17.6	—25.6	— 8.0
	Crystal 10 cm below	—14.0	— 5.9	—23.2	—28.0	

ever, it may be that only a fortuitous selection of patients prevented the observation of larger variations with crystals at positions 1, 3, 5 and 7, since considerably larger variations are observed with crystals at positions 2, 4 and 6.

Inherent uncertainty in measurement with a multiple-crystal array

It can be seen by visual analysis of the multiple-crystal array that the total counting-rate will vary greatly as a function of the location of the material in the body, even if the assumption is made that the body is the same thickness and size along its entire length. This fact can be seen quite easily from Fig. 3. Assume that radioactivity is located directly under crystal No. 4, the centre position. Crystal 4 will detect the largest number of counts, because of its proximity to the source. To a first approximation, crystal 3 will detect the same number as crystal 5 but both will detect considerably less than crystal 4. The same can be stated for crystal pairs 2—6 and 1—7. Next assume that the activity is directly under crystal 1 (in

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the patient's head). The counting-rates of crystals 1, 2, 3 and 4 will correspond, respectively, to the counting-rates of crystals 4, 5, 6 and 7 under the above conditions. However, the counting-rates of crystals 5, 6 and 7 (second case) will be considerably less than those of crystals 1, 2 and 3 (first case).

It is also obvious that the total counting-rate will vary as a function of the patient's height. Consider again the counting-rate of crystal No. 4. The activity in the head and feet of a short person will be counted much more efficiently than that in the head and feet of a tall person, because of the different distances involved. Since the same reasoning can be applied to the counting-rates of any other crystal position, it follows that the counting-rate must vary as a function of the patient's height. These facts demonstrate that the distribution of radioactivity in a phantom used to calibrate the multiple-crystal array must be very close to the distribution in the human; otherwise, large errors will result.

Theoretically, both of these effects can be reduced by extending the line of crystals beyond the head and feet of the patient. Unfortunately, these crystals will not be used very efficiently since their counting-rates will be quite low.

Problems of calibrating a total-body counter

The problems involved in calibrating a counter will be dealt with only briefly, since they have ben discussed elsewhere [1]. Naturally, the magnitude of the problems will be greater when higher accuracy is required.

The counter may be calibrated by administering known amounts of radioactive material directly to patients. While this method yields more accurate results than other methods, it is often not feasible either because of the chemical toxicity or of the biological half-life of the element. For example, it is not possible to administer enough normal K to a human to calibrate the counter. In the cases discussed above, K^{42}, an isotope of the same element, was given to the subjects. When other isotopes of the same element are used, it is very important that the energy of the gamma ray be very close to that of the one being studied. An absolute error of about 2% exists in the K calibrations given in Table XIII because of the higher absorption of the 1.46-MeV gamma ray from K^{40} than of the 1.52-MeV gamma ray from K^{42}. The magnitude of this error would be considerably larger if the difference in energies were greater.

If neither the element nor an isotope of the element can be administered to the patient, it is necessary to resort to the use of radioactively loaded phantoms. When a whole-body counter is calibrated by loading a phantom, an average calibration constant is assumed—if not for all patients, then at least for patients of one particular build. The dependence of counting-rate upon body thickness can be eliminated to some extent by using phantoms of different thickness. However, since the effective thickness of the body varies from the head to the feet, such refinements are still only approximations.

Calibrating the tilting chair

The tilting chair can be calibrated by using phantoms. The measurements presented in Table I demonstrate that a constant ratio (within $\pm 2\%$) exists between the counting-rates of a K^{42}-containing subject in the tilting chair and on the 1.75-m

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arc. The same ratio exists for all energy bands from 300 keV up if the same crystal is used for both measurements*. Measurements made with the same patients on the 1-m arc and the tilting chair have demonstrated that the average tilting-chair counting-rates are 3.9 times that of the 1-m-arc counting-rates. This ratio has been found to apply to both Ra and K.

The tilting chair is empirically calibrated as follows. A known quantity of the isotope present in the human is placed in the centre of a phantom 14 cm thick. The phantom is placed directly below the crystal with the distal face of the phantom 1 m from the face of the crystal. The calibration factor (in counts/min μc) is obtained by multiplying the observed counting-rate by 3.9 and by dividing it by the source strength.

Experience has shown that calibrations with phantoms may lead to errors of $\pm 5\%$ in measurements of alkali metals and of $\pm 10\%$ in measurements of the alkaline earths within the human body. It does not seem possible to calibrate the tilting chair in this fashion for materials which concentrate in specific organs, such as Co^{60}-labelled vitamin B_{12} and thorium or other colloidal solutions which go preferentially to the liver.

Conclusions

The choice of whole-body counter will depend upon the particular studies to be made. For certain studies, the tilting chair has advantages over other types of counter. These advantages are: (1) smaller inherent uncertainty (i. e., higher accuracy) in the measured value when an average calibration constant is used and the patient is not given a calibrating tracer; (2) greater ease and speed of operation, since only one crystal need be calibrated; (3) more reliable results, since mixing circuits are not required; and (4) equal or higher counting-rate in the photopeak and considerably lower counting-rate at lower energies than those observed with multiple-crystal arrays if the same volume of NaI(Tl) is used. This last advantage leads to more economical use of crystals.

The advantages of the multiple-crystal array are that: (1) a higher total counting-rate can be obtained if large crystals are used; and (2) something can be learned about the distribution of the isotope in the human if the outputs of the different crystals are sorted and recorded separately.

The disadvantages of the multiple-crystal array are: (1) the longer time required to calibrate the large number of crystals; (2) the relatively complex mixing and gating electronic circuits required either to add the various crystal outputs into one composite spectrum or to store the output of each crystal into a different section of the magnetic memory of the analyser; (3) the expense of the large crystals; (4) the large inherent uncertainty for measurements of alkaline earths unless several crystals are used; and (5) the greater possibility of a false indication of the presence of other isotopes as a result of a shift in the energy calibration of one of the crystals in the array.

* The ratios in Table I for the photopeak band differed from those for the Compton band because they were obtained with two crystals whose resolution differed considerably. The average ratios between the two groups do not agree because the resolution of the crystal used on the 1.75-m arc changed radically (because of the failure of one of its three photomultiplier tubes) during the weeks between the two groups of measurements.

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The main disadvantage of the multiple-crystal array, i. e., the large inherent uncertainty, will not exist in those studies in which isotopes are administered to patients, since the patients themselves will serve to calibrate the counter. However, the extra sensitivity of the multiple-crystal array is not always needed in these cases.

The one potentially important advantage of the multiple-crystal array is that it gives an indication of the distribution of activity in the body. This may be important in the study of the metabolism of different elements. However, to obtain this information, the counting-rate of each crystal must be determined. This can be accomplished by recording the total number of counts from each crystal (with either a scaler or a single-channel analyser) if only one isotope is administered to the patient. If two isotopes are administered at the same time, the actual spectrum from each crystal must be analysed and stored independently. This requires one multi-channel analyser for each crystal in the array or an appropriate electronic network to sort and store selectively the output of each crystal in a particular section of a magnetic memory.

Since the actual counting-rate observed from the patient increases at least in proportion to the crystal volume, the practicability of making four or five separate measurements with one large crystal, e. g. with an 11.5-in × 4-in crystal, instead of one simultaneous measurement with four 6-in × 4-in crystals, should be carefully considered. The total time needed to count the patient, except for the time to print out the data, will be the same if the total volume of NaI(Tl) is constant (assuming the crystals are the same thickness), and considerably less time is required to calibrate one crystal than, say, four. In practice, moreover, adequate diagnostic information about the distribution of the element in the body can be obtained only by scanning the patient with a collimated crystal. All things considered, the most economical and versatile combination seems to be a single large crystal to be used both above the tilting chair for whole-body measurements, and at successive positions above the bed, preferably with a collimator for precise localization.

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