An Organic Plastic, Localizing Whole-Body Counter

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Whole-body counters designed for human use have been, in general, variations on one of two basic designs: A NaI system typified by the Argonne National Laboratory developments (1, 2), or the liquid scintillation system pioneered by the Los Alamos Scientific Laboratory (3,4). Sodium iodide systems usually employ a single radiation detector, although as many as four have been used (5). In the usual single-crystal arrangement the patient is customarily seated in a tilting chair and viewed by the crystal from above (5). The "arc" technique has also been employed, with the patient forming a portion of a circular arc with the crystal at the center.

In a 4 π liquid counter the patient is essentially surrounded by the scintillating solution. A large fraction of the gamma rays issuing from the patient will be intercepted by the detector which has no ability to localize the point of origin of the radiations.

Each of these designs has some disadvantages for use in clinical medicine. Some seriously ill patients cannot assume the configuration required for either the chair or the arc techniques; some will refuse the restricted environment of the 4 π liquid counter.

Many clinical applications would benefit from the use of a counter that had some ability to localize the source of the gamma radiations. The detailed spatial resolution obtainable with a heavily collimated scanner would be a most desirable feature but is difficult to achieve in a whole-body counting situation. Localization to an organ the size of the spleen or heart would be a useful compromise between the two extremes.

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CONSTRUCTION

The 2 π organic plastic scintillator to be described was designed to eliminate some of the less desirable features inherent in other counter types when they are used to count seriously ill or mentally disturbed patients. A multidetector system was installed to provide some degree of spatial localization.

Counting in a linear, supine position was adopted because it seemed to permit the least traumatic transfer from bed to counter and return. A device to transfer patients safely and easily to and from the counter is an essential part of the system. This purely mechanical device need not be described here.

The patient is supported in the counter by a stainless steel semicylinder or trough 21 inches in diameter and 78 inches long (Fig. 1). These dimensions
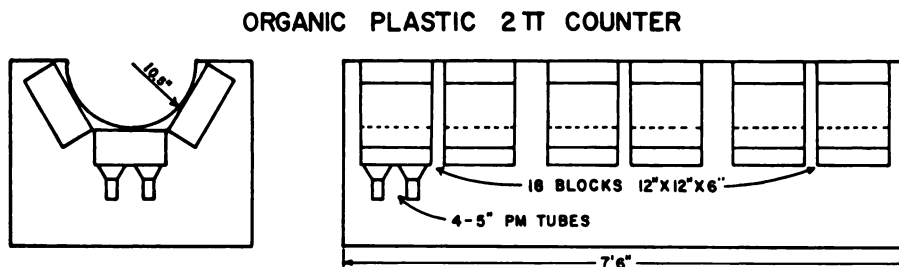
ORGANIC PLASTIC 2 π COUNTER

Fig. 1. Geometrical arrangement of the 18 plastic detectors and 72 photomultiplier tubes.

have been found acceptable for patients weighing up to 350 lbs., although the obese patients extend above the trough and require special calibration procedures. The stainless steel trough and the supporting members introduce absorption and scattering, and hence were made as light as was consistent with strength. Two structural members supporting 0.025 inch thick steel have proved adequate.

The detector consists of 18 blocks of an organic plastic scintillator[1] each 12 inches × 12 inches × 6 inches. Three blocks tangent to the exterior just circumscribe the semicylinder. Three rows of six blocks each, separated slightly to accommodate structural members, extend to a length of 76 inches. Organic plastic detectors were chosen because they have an energy resolution and absorption characteristics comparable to liquids, and offer distinct advantages in stability and maintenance in a clinical environment.

There are several advantages to a 2 π geometry for counting ill or disturbed patients. The 2 π counter, placed inside a steel shielded room 12 feet × 8 feet × 8 feet is much more acceptable than the restrictions of a 4 π environment. With a total detector volume of nine cubic feet sensitivity is adequate for counting naturally occurring ^{40}K or any of the gamma emitters commonly administered in medical practice.

Four five-inch diameter photomultiplier tubes were optically coupled to the polished outer face of each plastic block. Phototube performance was roughly

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matched by the use of two voltage supplies set 100 V apart. Finer adjustments were made with voltage and focus controls on each individual tube. The signals from each group of four tubes were summed and amplified before leaving the shielded room. Final equalization was made by 18 trimmers in the outputs of the main amplifiers.

The 18 amplified signals were combined in a linear summing amplifier and passed on to four single channel pulse-height analyzers, connected in turn to four scalers with manual readout. Any one of the 18 signals can be put into or withheld from the summing amplifier by a front-panel switch.

The amplified signals, both before and after analysis, can be fed into the multichannel pulse-height analyzer used in an adjoining NaI whole-body counter system. With this arrangement, rapid and precise discriminator settings can be made to accept any desired portion of an energy spectrum. Figure 2 shows a
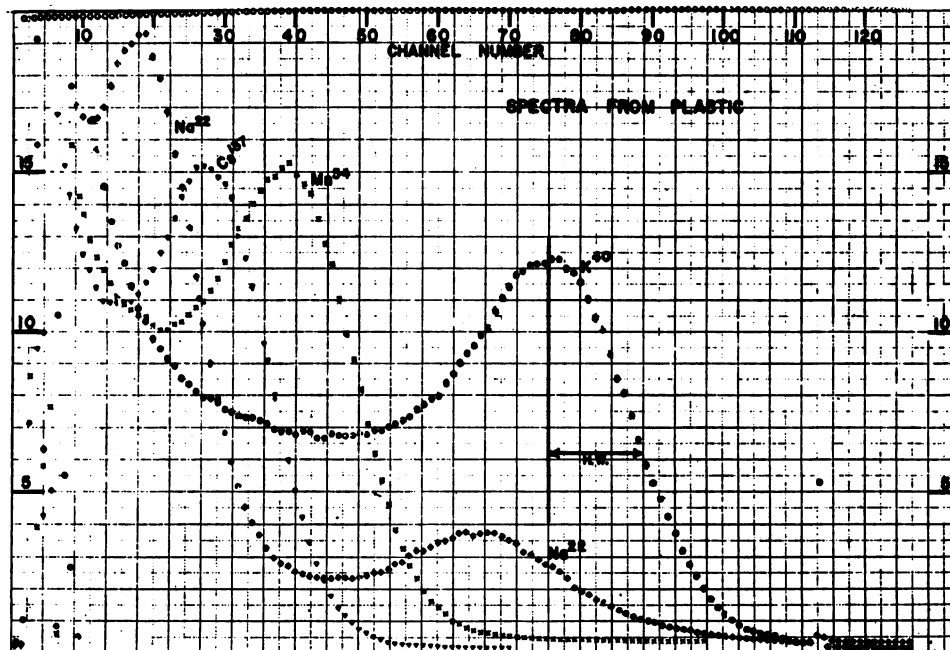

Fig. 2. Typical spectra recorded from a single plastic detector with inherent scattering only. The ordinate scale is in arbitrary units and the relative heights of the four spectra are without significance.

series of unanalyzed spectra as recorded from a single detector with an analyzer sensitivity of 15.6 KeV/channel. Each of the nuclides depicted in Fig. 2 emits a single gamma ray but ^{22}Na also gives rise to 0.51 MeV annihilation photons and hence a small but appreciable sum peak appears at 1.79 MeV.

ENERGY RESOLUTION

Photoelectric absorption is the predominant process by which gamma rays transfer their energy to a high atomic number detector such as NaI. In photoelectric absorption the ejected electron carries off all of the energy of the incident photon, except for that required to remove the electron from its parent atom.

A beam of monoenergetic photons produces an essentially monoenergetic population of electrons. Statistical fluctuations in the scintillation process and in the photomultiplier tube broaden the pulse height distribution to form the well-known photopeak.

Compton scattering is the predominant absorption process in a low atomic number detector such as an organic plastic. Only a portion of the energy of the original photon is transferred to the electron that produces the scintillation; the remaining energy is carried off by a scattered photon that has a relatively low probability for absorption in the detector. The energies of the incident and scattered photons are related to the scattering angle θ by the Compton equation which can be written:

$$\frac{1}{E} - \frac{1}{E^1} = \frac{1}{M_0C^2}\left(1 - COS\,\theta\right) \tag{1}$$

Where E is the primary photon energy and E^1 that of the scattered photon.

The broad peaks seen in Fig. 2 correspond to the energies imparted to Compton electrons when the original photons undergo single scattering through the maximum possible angle of 180°. The less probable Compton interactions at smaller scattering angles are responsible for the lower-energy portions of the spectra.

Figure 3 shows the energy of the Compton electron, calculated by Eq. (1) for maximum scattering, plotted against the analyzer channel number in which the corresponding spectral peak appears. The response of the plastic detector appears to be strictly linear with the energy absorbed in it, at least down to the 0.187 MeV deposited when a photon from ^{51}Cr undergoes maximum scattering.
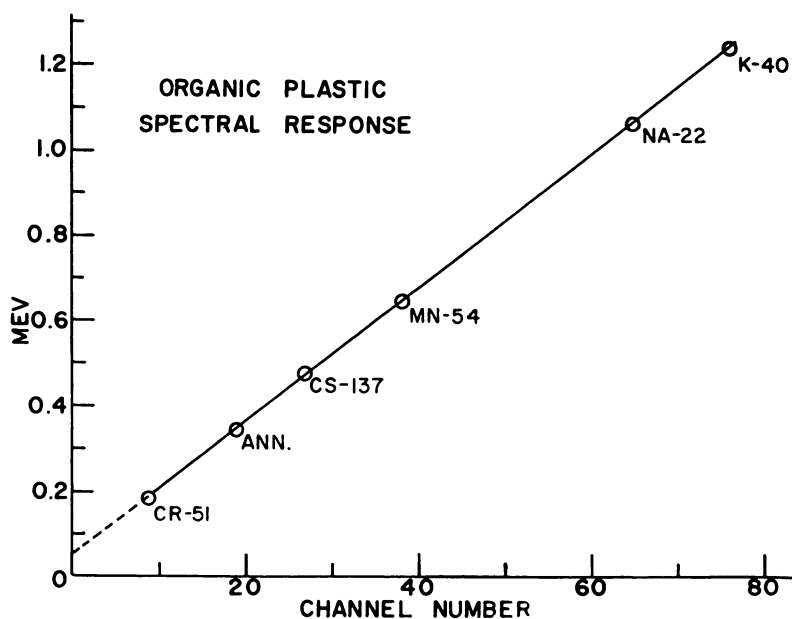

Fig. 3. Calculated energy imparted to the electron in a maximum-angle Compton process plotted against the channel number in which the corresponding spectral maximum appears. ANN is the point representing the scattering of the 0.511 MeV annihilation photons from ^{22}Na.

An extrapolation of the response curve to zero light output (channel zero) leads to an intercept of about 50 keV on the energy axis. This value agrees well with the value found by Burch (6), who explained the intercept as a failure of linear response to the high values of linear energy transfer (LET) from very low-energy electrons.

The energy resolution of an organic plastic scintillator is decidedly inferior to that obtainable with a high atomic number detector such as NaI. Energy resolution is customarily measured by the half-width taken on the high-energy side of the spectrum at half-maximum height (Fig. 2). Figure 4 shows a plot of the measured half-widths of the plastic detector, expressed as a percentage of the energy at the peak. Another common measure of energy resolution, the peak-to-valley ratio, is plotted in Fig. 5. Note that in both Fig. 4 and 5 the point representing the 1.28 MeV gamma ray of ^{22}Na is displaced from the smooth curve connecting the other points. These displacements, in the direction of poor resolution, result from the presence of the energy sum of a gamma ray and an annihilation photon simultaneously absorbed.

The data from which Figs. 4 and 5 were constructed were obtained with a single organic detector under scattering conditions comparable to those for a typical adult human. Practical difficulties of circuit alignment, and fluctuations in preamplifier gains prevent the attainment of single-detector resolution when all
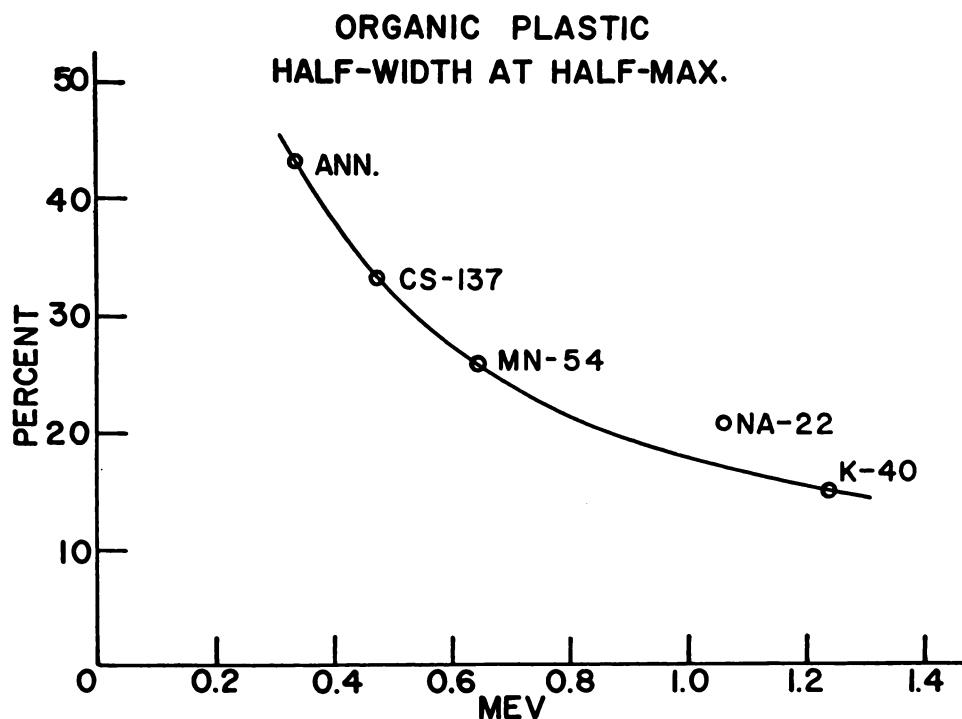

Fig. 4. Spectral resolution expressed by the half-width at half-maximum. The plot is in terms of the energy imparted to the Compton electron and not the energy of the original photon. The displacement of the point representing ^{22}Na is due to broadening from the sum peak.

18 detectors are used. A half-width of 16 per cent can be obtained with a single detector at the 1.46 MeV ^{40}K energy; the 18-block half-width will not exceed 20 per cent for many months after a careful circuit alignment.

The energy resolution of an organic detector decreases rapidly with decreasing photon energy while at the same time the background is increasing. These two effects limit the use of the plastic system with clinically acceptable doses to nuclides having gamma rays of 0.3 MeV or more. This low-energy limitation has not proved to be serious in practice. Either ^{51}Cr or ^{131}I can be counted comfortably and out of some 1600 requests per year from the clinical and investigative staff only ^{57}Co and the thyroid localization of ^{131}I have required the use of the NaI detectors.

We have had no requirement for double label counting although our patients are drawn from a wide clinical spectrum. Because of the predominance of Comp-
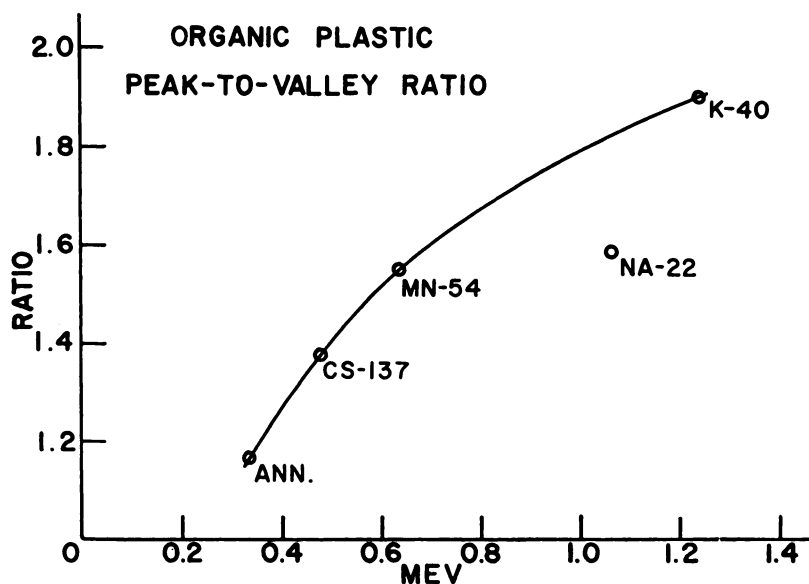

Fig. 5. Spectral resolution expressed by the peak-to-valley ratio plotted in terms of the energy imparted to the Compton electron.

ton scattering, there is some contribution from ^{40}K into all lower-energy channels but this contribution is usually too small to interfere, and in any case it can be subtracted out with the background count.

SPATIAL RESOLUTION

Figure 6 shows the response of one set of organic detectors as a ^{137}Cs source is moved axially through the counter under approximately normal scattering conditions. As expected the differential response of the individual detectors is most marked when the source is as close as possible to one of them. Lateral spatial discrimination is lost when the source is on the axis of symmetry, Fig. 6-3.

The data shown in Fig. 7 were also obtained under scattering conditions approaching those obtained with a human subject. The ^{137}Cs source was moved through a narrow trough of water which was surrounded by a cane sugar scat-

tering phantom. Again the greatest spatial differentiation is obtained when the source is at the point of closest approach. The combined response of the three detectors in this group shows variations of about 10 per cent from the mean for a peripheral source. When the source is retracted 10 cm the combined response is essentially constant, although the individual detectors still show a considerable ability to differentiate. Obviously, the response of these detector configurations is a complex function of source position. Careful consideration must be given to calibration procedures if the count rates are to yield meaningful results in terms of body burdens.

CALIBRATION

All calibrations of the 2 π plastic scintillator have been based on measurements made with suitably constructed phantoms. Cane sugar appears to be entirely free of gamma ray emitters and is a satisfactory inert material for constructing the calibration phantoms. The sugar is most conveniently used in the two-pound boxes that are supplied commercially.

The calibration procedure is relatively simple when all 18 detectors are being used to determine a widely distributed nuclide such as ^{40}K or ^{137}Cs. Each of the boxes making up the active part of our ^{40}K phantom contains 8.40 gms of K as KCl in a thin-walled plastic tube. Each corresponding box of the ^{137}Cs phantom contains a glass ampoule with a ^{137}Cs solution which emits on the order of 10^2 gamma rays per second. One hundred "active" boxes are available for each nuclide being studied; 200 lbs of sugar with no added activity are available for simulating nonactive tissues such as fat. These materials have been used in the construction of phantoms up to weights of 350 lbs.

For more commonly encountered sizes of humans, calibration curves of counting efficiency as functions of height and weight have been developed from
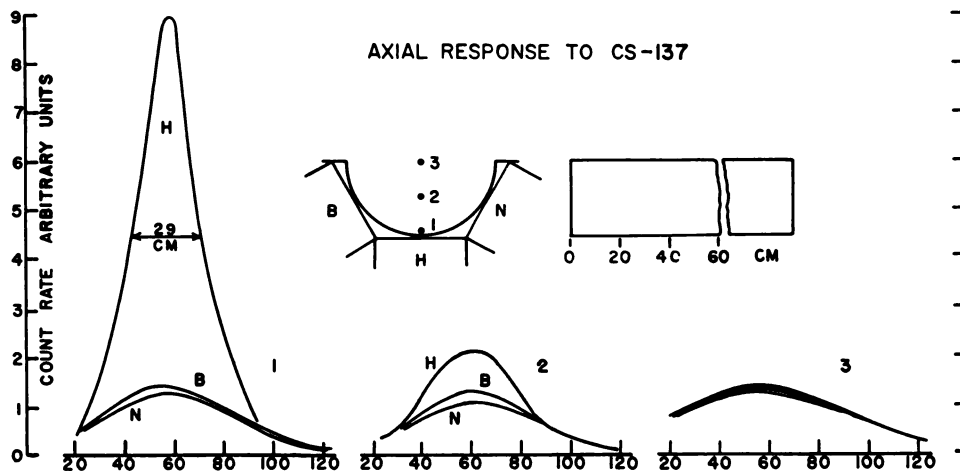

Fig. 6. Response of single detectors (B, H, and N) to a ^{137}Cs source moved axially along the counter. Scattering conditions approximated those for an adult human.

measurements on sugar phantoms (Fig. 8). The counter stability has permitted the use of one set of curves for as long as a year. Day-by-day checks on the counter sensitivity are made by appropriate sources uniformly distributed along the axis of symmetry. Measurements made on human "standards" have been in excellent agreement (usually within 2 per cent) with the results from other counter installations.

The response of radiation detectors in the 2 π configuration used here depends upon the location as well as the amount of the emitting nuclide. This characteristic is shared to a greater or lesser extent by each of the detector arrangements in common use. When individual recordings are made from multiple detectors, the final interpretation of the measurements must be made in terms of the calibrating phantom rather than in terms of the detector response.

Consider for simplicity a situation in which two detectors, 1 and 2, view a human subject. If the geometrical responses of the two detectors are dissimilar,
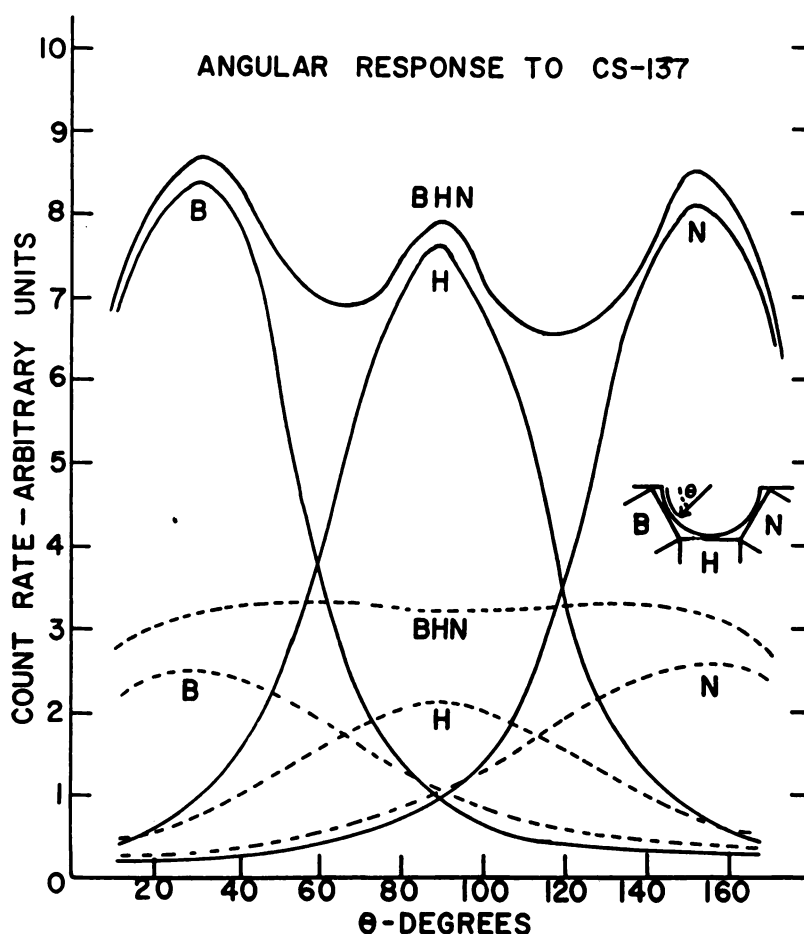

Fig. 7. Response of single and multiple detectors to a ^{137}Cs source moved circumferentially across the midplane of the detectors. The solid curves were obtained with the source as close as possible to the supporting trough; the dotted curves were obtained with a 10 cm separation. Maximum scattering conditions.

they can be used to determine the body burdens of one or more gamma-emitting nuclides in two body compartments. We will limit the discussion to a single nuclide in two compartments, A and B, which for the moment are completely arbitrary.

If we denote each net count rate by C and each compartment burden by Q with appropriate subscripts we have:

$$C_1 = aQ_A + bQ_B \qquad (2)$$

$$C_2 = cQ_A + dQ_B \qquad (3)$$

The four coefficients a, b, c, and d are in the nature of detector efficiencies. When these coefficients are known, Q_A and Q_B can be readily determined from a simultaneous solution of (2) and (3).

$$Q_A = \frac{dC_1 - bC_2}{au - bc} \qquad (4)$$

$$Q_B = \frac{aC_2 - cC_1}{ad - bc} \qquad (5)$$

The coefficients are readily obtained by constructing a phantom in which a known amount of the nuclide in question is put first in compartment A, then in compartment B. The first phantom measurement serves to determine coefficients a and c, the second b and d.

Each compartment is chosen to represent that organ or system whose active isotope burden is desired. As far as possible, the calibrating nuclide is distributed
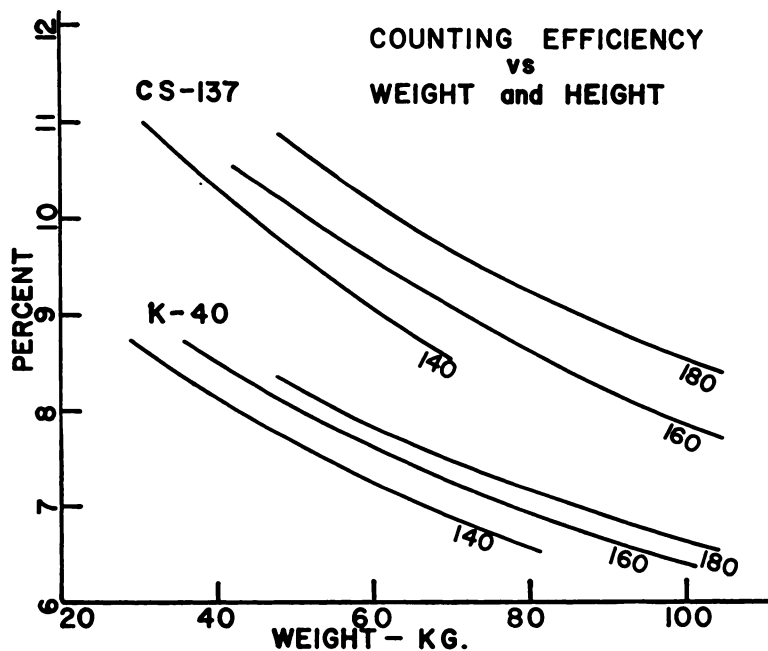

Fig. 8. Counting efficiency as a function of body height and weight. Individual phantoms are constructed for persons beyond the limits of the working curves shown.

within each compartment as it would be in the human situation. In each calibration inert scattering material is placed in the inactive compartment.

A measurement made on a human subject gives values of C_1 and C_2 which yield values of Q_A and Q_B. These values must be interpreted in terms of the phantom configuration only, without reference to the detecting geometry of 1 or 2. For the greatest accuracy, it is desirable to choose detector configurations that will maximize the differential response from the two compartments, but this is not a necessary requirement. The degree to which the measurements yield true body burdens depends primarily upon how well the phantom construction duplicates the distribution actually existing in the body.

In principle, this method of localization can be extended to three or more compartments and to the simultaneous determination of two or more radioactive nuclides. The number of independent detectors must be equal to the number of compartments, and the spectral resolution of the system must be sufficient to permit differential counting of the individual nuclides.

The two compartment model and calibration procedure has been tested by measuring the partial-body ^{40}K and ^{137}Cs in two subjects serving as controls for a collateral study. In this study it was desired to determine the K and Cs burdens in the upper and lower portions of the body. A plane through the iliac crests was chosen as the boundary between the two compartments.

Counts were taken at almost daily intervals with each subject placed so that the iliac crests coincided with the plane separating the two midcounter sets of detectors. Two of the channels were optimized to detect ^{40}K and ^{137}Cs, respectively. A 10 minute count was first taken from all 18 blocks in our standard whole-body geometry. Consecutive 10 minute counts were then taken from an upper set of nine detectors (C_1) and from a lower set of nine detectors (C_2).

Values of total body burdens (K_T and $^{137}Cs_T$) were calculated from measurements made on a standard one-compartment phantom known to produce results in excelent agreement with those from other laboratories. A two-compartment phantom, split at the position occupied by the iliac crests, provided data for the two-compartment calibrations.

The results from one of the normal subjects is shown in Figs. 9 and 10. There was no reason to expect a trend in the body burdens during the 21 days of study, so mean values and their standard deviations were calculated. These values are given in Table I. Figures 9 and 10 display the mean values and the standard deviations for single determinations.

TABLE I

MEAN BODY BURDENS OF K AND Cs

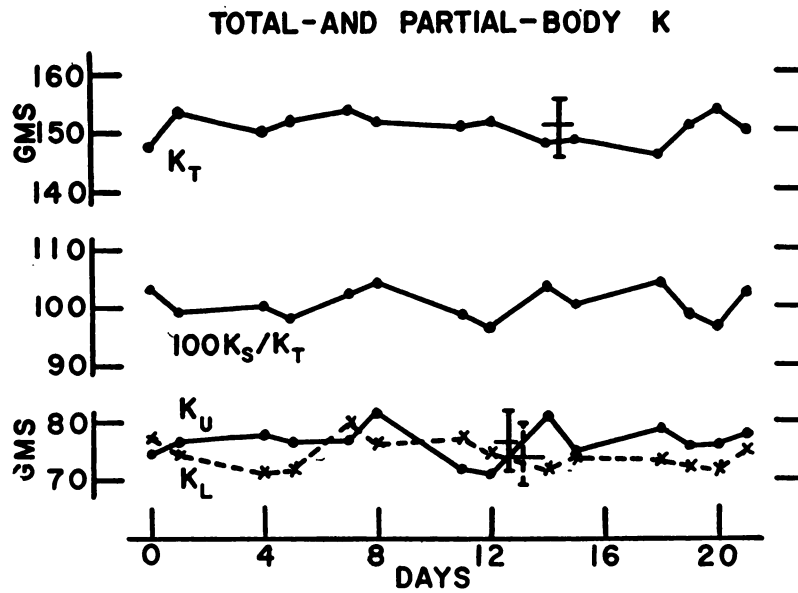|	Grams	Nanocuries
Whole body	K_T 150.2 ± 0.67	Cs_T 17.7 ± 0.12
Upper portion	K_U 76.2 ± 0.78	Cs_U 8.4 ± 0.082
Lower portion	K_L 73.4 ± 0.70	Cs_L 9.3 ± 0.093

TOTAL-AND PARTIAL-BODY K

Fig. 9. Potassium distribution in an adult on normal diet and exercise. The mean and the standard deviation for a single determination are shown for each compartment.
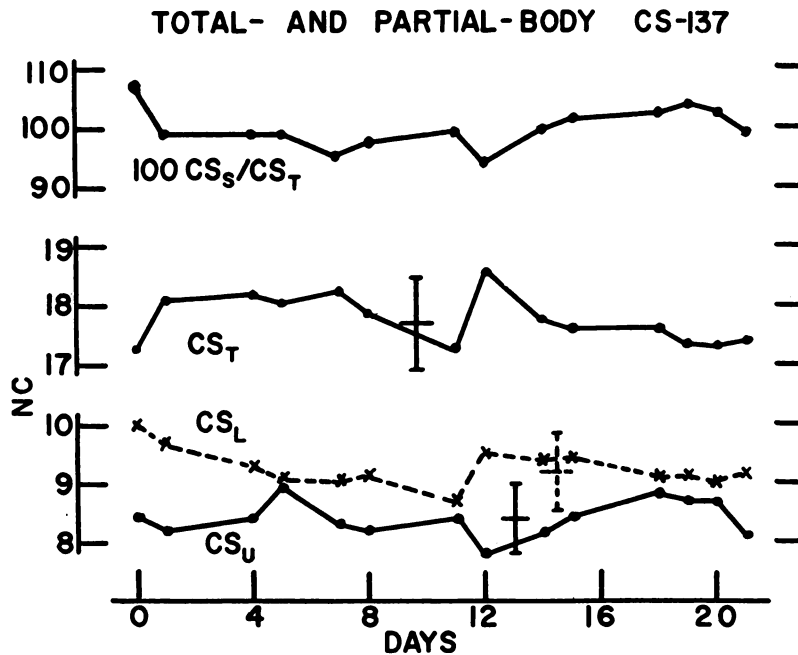
TOTAL- AND PARTIAL-BODY CS-137

Fig. 10. Distribution of ^{137}Cs in an adult on normal diet and exercise. The mean and the standard deviation for a single determination are shown for each compartment.

One check on the accuracy of the method can be obtained from a comparison of the sum of the two partial values ($K_S = K_U + K_L$) with the total value which was obtained from an independent phantom construction. These comparisons are made in Figs. 9 and 10 as the ratio of the sums to the totals, each expressed as a percentage. In the case of K, the maximum departure from the expected value was only four percent. The corresponding value for Cs was about seven percent, which is not surprising since each of these values depends upon corrections for the ^{40}K activity as well as upon the measurements for ^{137}Cs itself.

The lack of agreement represents the combined effects of statistical variations in counting rates, errors in subject placement, and perhaps some short-term changes in the compartment burdens. In this connection it should be noted that the mean K-Cs ratios in the two compartments are significantly different.

CONCLUSIONS

The energy resolution of organic plastic scintillators is quite adequate for the assay of most of the radioactive nuclides commonly used in clinical and experimental medicine. No difficulty has been encountered in a period of over two years in maintaining the detecting efficiency of an 18 detector system employing 72 photomultiplier tubes. The ability of a multidetector system to localize depends primarily upon the calibration procedures and only secondarily on the detector response.

Multicompartment measurements have proved feasible in simple configurations and can be extended to organs and more complex nuclide distributions.

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