BODY POTASSIUM MEASUREMENTS WITH A TOTAL-BODY COUNTER

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Changes in body potassium may be of importance in nutritional disorders, chronic illness or long-term treatment with kaliuretic agents, such as steroids or diuretics. Direct measurements of total-body potassium have recently become feasible with the development of sensitive, well-shielded body counters (*1–5*). Determinations of the naturally occurring radioisotope of potassium ^{40}K offer the advantages over metabolic balance studies or exchangeable potassium techniques that measurements can be made frequently during indefinitely long periods of time and results may be immediately available.

Of the two major types of radiation detectors, the liquid scintillator and the sodium iodide crystal, the latter permits more precise gamma-ray spectroscopy. A variety of counting geometries have been used (*6–9*); for clinical studies a particular geometry should result in minimum variability in counting rate due to differences in body build or changes in distribution of body potassium in a subject. To provide for such effects, a scanning geometry has been developed and a correction factor obtained for calculations of body potassium content.

METHODS

The whole-body counter consists of two matched 4 x 8-in NaI(Tl) crystal detectors mounted in a 12 x 7 x 8-ft room constructed of 9-in.-thick steel walls. Pulse-height analysis of the signal from the two detectors was performed with a 400-channel pulse-height analyzer. The measurements consisted of counts per pulse-height interval (gamma-ray energy interval) as a function of pulse height (gamma-ray energy) from the detectors arising from crystal absorption of gamma rays from disintegrating ^{40}K or ^{42}K nuclei.

The sum of the counts in each of two pulse-height regions for each radioisotope was used in the analysis. One consisted of the photopeak which included more than 95% of the unscattered photons whose energy was totally absorbed in the NaI(Tl) crystals. The other was contiguous with the photopeak region (called Compton region) and immediately below it in the energy range. This region included photons from Compton scatter in the source (subject or phantom) and energy losses from the NaI(Tl) crystal. A lower limit pulse-height cut-off corresponding to 1.00 MeV was chosen for the Compton region to preclude the possibility of radioactivity from fallout products, e.g., ^{137}Cs and ^{95}Zr, being included in the measurement.

Geometry. Two geometries were used (Fig. 1). Potassium-42 doses given to subjects and ^{42}K aliquots subsequently used in phantom measurements were measured in a static geometry (^{42}K syringe) in a 5-ml disposable syringe placed on the subject bed 35 cm from the plane defined by the crystal faces and on a vertical line midway between the two crystals.

Subjects were counted in supine and prone positions with their vertex at the −82 cm longitudinal position with a dynamic "scanning" geometry in which the crystals move relative to the bed with uniform horizontal velocity as defined by the dotted lines traced by the center of each crystal. The crystals remain separated by 105 cm and each moves 104 cm, starting at one of its traces. Measurements of counting rates from a point source of ^{42}K were made in air along a longitudinal line 10 cm above the subject bed and in the vertical plane defined by the crystal trace.

The same "scanning" geometry was used for measurements of counting rates from a point source in a water phantom. The phantom was rectangular and measured 25 cm perpendicular to the figure plane and 180 cm in the longitudinal direction; its thickness was variable. Its center was on the vertical plane defined by the crystal centers, at the 0 cm longitudinal position and at a distance equal to one-half of its thickness above the subject bed. This center defines the origin of an x,y coordinate system (y-axis vertical and x-axis in the longitudinal direction) to which phantom point-source measurements are referred. Point-source measurements made along the x-axis and at other points on the x,y plane are used to elucidate the variation of sensitivity of the counting system with geometrical position and attenuation.

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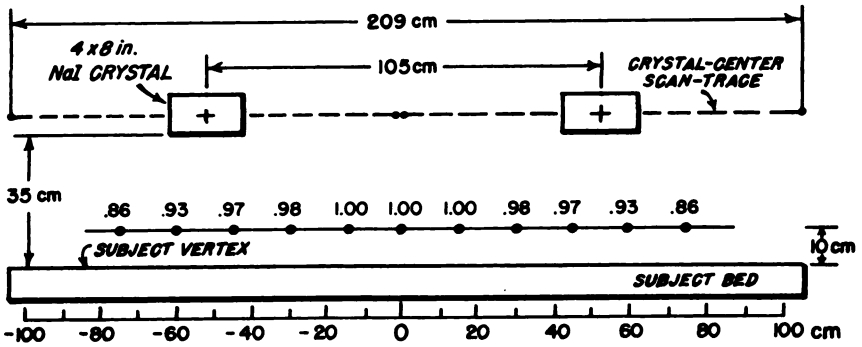

FIG. 1. Scanning-bed geometry. Crystal centers are maintained 105 cm apart and 35 cm above subject bed. In scanning mode, each crystal scans distance of 104 cm. Total scan length is 209 cm. Counting position for ^{42}K syringes and ^{40}K standards is at bed surface at 0 cm with bed stationary. Line of figures shows sensitivities in air 10 cm above subject bed.

Counter calibration. The method of calibration of the counter for *in vivo* determination of ^{40}K is similar to that used by Miller and Marinelli (*6,7*) and others (*8,9*).

A tracer dose of ^{42}K to be given to a subject or an aliquot of ^{42}K to be used for phantom measurements was counted in the static geometry (^{42}K syringe). This permitted measurement of each calibration dose without "scanning." The ratio of counts in the "scanning" geometry to counts in the static geometry was determined by intravenous injection of the tracer dose of ^{42}K into a subject or by mixing the aliquot of ^{42}K in the water phantom and counting subject or phantom in the scanning geometry. The dose of ^{42}K in the subjects was corrected for urinary excretion of ^{42}K during the study intervals of 2 and 24 hr after injection. All subject counting rates were the arithmetic mean of supine and prone counting rates. A half-life of 12.5 hr was used to correct all measurements for decay.

The same water phantom was used for ^{40}K calibration with the admixture of 56,000 mEq reagent grade KCl in solution. If the counting characteristics of the subject and the phantom were identical, as shown by ^{42}K measurements, then the ratio of ^{40}K counts in the subject to ^{40}K counts in the phantom could be applied to the potassium content of the phantom to give body potassium content directly, i.e., 56,000 mEq x (^{40}K subject)/(^{40}K phantom). As this is not the case, this result is corrected for the difference between ^{42}K counting in the phantom and in the subject, normalized in each instance by counting dose or aliquot of ^{42}K in the static geometry (^{42}K syringe). Because the phantom geometry is constant, the values for ratio of ^{42}K phantom/^{42}K syringe and for ^{40}K phantom are constants. Body potassium is then determined from the expression

$$K^+ \text{ (mEq)} = \frac{^{40}K \textit{ in vivo} \text{ (cpm)}}{^{42}K \textit{ in vivo} \text{ (cpm)}/^{42}K \text{ syringe (cpm)}} \cdot F \text{ (mEq/cpm)} \quad (1)$$

in which ^{40}K *in vivo* is the subject net ^{40}K, ^{42}K *in vivo* is the subject net ^{42}K, and

$$F \text{ (mEq/cpm)} = \frac{^{42}K \text{ phantom (cpm)}/^{42}K \text{ syringe (cpm)}}{^{40}K \text{ phantom (cpm)}} \cdot K^+ \text{ phantom (mEq)}. \quad (2)$$

Subject measurements. *In vivo* measurements on 11 male and seven female young, healthy adults were used to correlate the ratio ^{42}K *in vivo*/^{42}K syringe with an index of body build to which the counting response of the whole-body counter is sensitive. Body-count measurements were performed at 2 and 24 hr after intravenous injection of ^{42}K. Corrections were made for decay, residual syringe activity and urinary excretion.

In addition to 10 separate measurements of ^{42}K *in vivo*/^{42}K syringe and ^{40}K *in vivo* were made on separate occasions in the same subject. A patient with severe potassium depletion was measured repetitively (^{40}K *in vivo*) during a period of K^+ loading to compare body potassium determinations with cumulative K^+ retention on metabolic balance. Replicate measurements of ^{40}K *in vivo* were made on 27 normal subjects. The body potassium of one subject, RG, was determined by other whole-body counting centers.

Measurements of the subjects' weights and heights were also recorded. The methods of statistical analysis of the subject count data by the Student t-test and chi square test are described in Snedecor (*10*).

RESULTS

Phantom studies. Figure 1 shows relative photopeak counting rates from a ^{42}K point source in air positioned at various points along the longitudinal axis. Similar results were obtained from a point source positioned on the same axis in a 20-cm-deep water phantom. In either case, the longitudinal variation in point-source sensitivity is less than ±5% from the mean value over a total distance of 140 cm (−70 cm to +70 cm).

Figure 2 shows the ratio of the arithmetic mean of the counting rates obtained from a ^{42}K point source placed equidistant above and below the x-axis at $x = 30$ cm (^{42}K photopeak conjugate counts) to the static counting rate from the same source (^{42}K syringe) as a function of the absolute value of y for different phantom thickness. The taking of this mean simulates the mean of supine and prone counts obtained with subjects. Measurements at other longitudinal positions show similar behavior.

To indicate the relative sensitivity to changes in the distribution of continuous vertical sources, the response to homogeneous line sources of varying lengths in water phantoms and along a line parallel to y axis at $x = 30$ cm was calculated from the point-source data (Fig. 2). Each line was bisected by the x axis, and the lengths varied from 100 to 50% of each phantom thickness. Thus for the 100% length the line source was homogeneously distributed in the phantom thickness, while for other lengths the distribution of the line source was homogeneous through a central region but absent above and below this region. With decreasing lengths of the line source relative to phantom thickness, the effect of increasing phantom thickness is reduced (Fig. 3).

Subject measurements. ^{42}K *in vivo*/^{42}K syringe varied as a function of the square root of subject's weight per unit height $(W/H)^{1/2}$, using photopeak counts alone or photopeak plus Compton counts (Fig. 4). The data were fitted by the method of least squares in terms of a polynomial* of $(W/H)^{1/2}$ yielding standard errors of $\pm 2.0\%$ and $\pm 2.2\%$, respectively. The two curves are essentially parallel. The two sets of data were obtained from the 24-hr

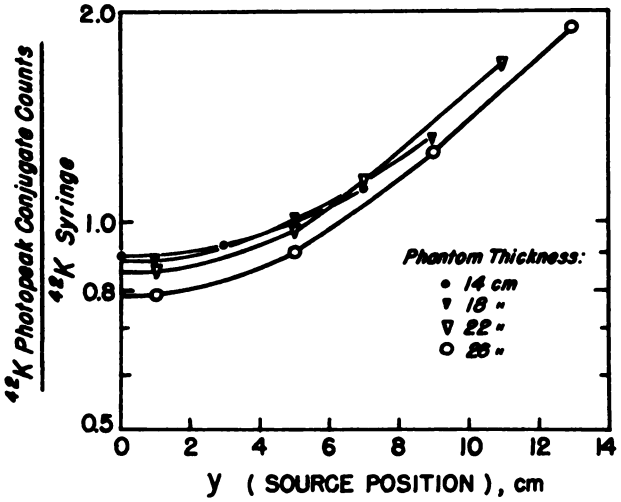

FIG. 2. Phantom study. Ratio of mean of counting rates from point source positioned at points equidistant above and below phantom midline (^{42}K photopeak conjugate counts) to counting rate from same source (^{42}K syringe) located at bed surface as function of distance of points from phantom midline (source position).

measurements on the same 18 subjects. The 2-hr count data (not shown) yield curves which were higher than the 24-hr count data by $2.3 \pm 2\%$.

^{40}K *in vivo*/mEq K^+ as a function of $(W/H)^{1/2}$ was calculated from

$$\frac{^{40}K \textit{ in vivo}}{K^+ \textit{ in vivo}} = \frac{^{42}K \textit{ in vivo}}{^{42}K \text{ syringe}} \frac{1}{F} \frac{\text{cpm}}{\text{mEq}}. \qquad (3)$$

Equation 3 is obtained from Eq. 1. When ^{42}K calibrations are used, the measured ratio ^{42}K *in vivo*/^{42}K syringe is substituted into Eq. 3 as indicated. When direct calibrations are not available, the ratio can be calculated from the subject's W/H as illustrated in Fig. 4. These results permit immediate calculation of a subject's body potassium from his ^{40}K counting rate and his body weight and height.

* These data were fitted by computer program with the cooperation of the Computing Center of Massachusetts Institute of Technology, Cambridge, Mass.

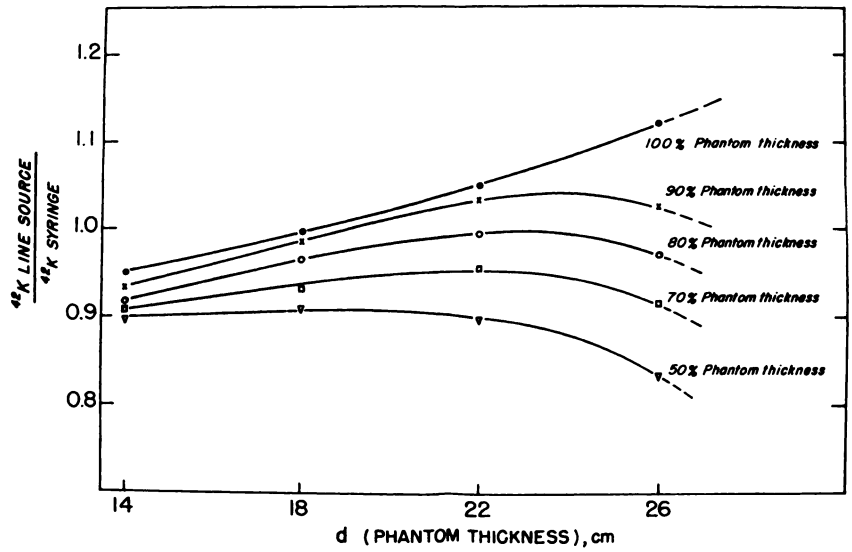

FIG. 3. Summary of phantom data indicates changes in value of ratio ^{42}K line source/^{42}K syringe on ordinate for changes in phantom thickness. Lines represent changes in ratio that would occur if there were homogeneous distribution of ^{42}K in various fractions of overall phantom thickness.

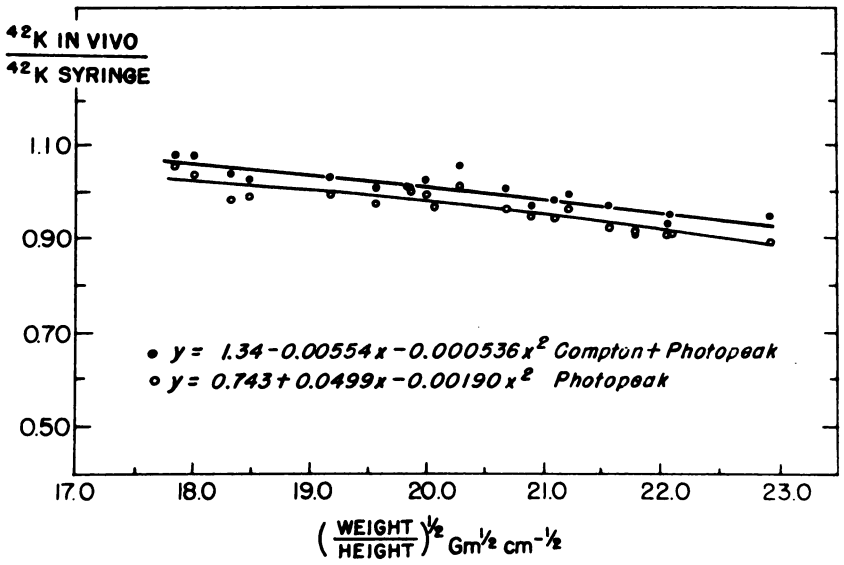

FIG. 4. Ratio of ^{42}K *in vivo* to ^{42}K syringe as function of subject $(W/H)^{1/2}$. Units of weight and height are grams and centimeters, respectively. Upper curve was determined for energy band extending from 1.00 MeV to 1.6 MeV and lower curve was obtained from 1.39 MeV to 1.66-MeV photopeak region at 24-hr post-injection of ^{42}K.

The values of total-body potassium obtained by the indirect method, using $(W/H)^{1/2}$ as the body build index (Fig. 4), were compared with those obtained by ^{42}K calibration in each of 24 subjects. $(W/H)^{1/2}$ values ranged from 18.5 to 25.0 $(gm/cm)^{1/2}$. Statistical analysis gave a chi square of less than 3.8 for all measurements.

Backgrounds and *in vivo* calibration. The body counter background gave values as follows: ^{40}K photopeak region, 138 cpm and ^{40}K Compton region, 156 cpm. The standard deviation of the background counts throughout the period of the investigation was within ±1%. The *in vivo* calibration gave values for F of 25.8 ± 0.7* (N = 107) and 17.2 ± 0.8* (N = 97) for the photopeak and photopeak plus Compton region, respectively.

Metabolic balance and replicate measurements. A cumulative potassium balance was carried out to compare metabolic balance and the total-body potassium measurement. During an 8-day period on a high-potassium diet, gains of potassium were noted by both methods: 220 mEq by total-body potassium measurement and 248 mEq by metabolic balance in 5 days and 400 mEq compared to 439 mEq, respectively, in 8 days. On the seventh day a serum potassium value of 4.1 mEq/L was found, compared to an initial value of 1.9 mEq/L. The apparent increase in body potassium was approximately 10% greater by metabolic balance than by body counting. With ^{42}K calibration, replicate measurements in the same individual gave an error of ±2.3% (standard deviation). Replicate ^{40}K measurements in 27 normal subjects were compared by chi square between individual measurements in each subject. In 24 of these, chi-square values were less than 3.8. In one, chi square had a value of 7.6 and in two others chi square had values of 15.2.

Total-body potassium measurements were made on Subject RG at various locations, as shown in Table 1. Good agreement was noted despite the various counting geometries used.

DISCUSSION

Body potassium can be measured by two methods: one requires ^{42}K calibration and one depends on previous calibration of the instrument and takes into account variations in ^{40}K counting resulting

TABLE 1. COMPARISON OF TOTAL-BODY POTASSIUM MEASUREMENTS IN ONE HEALTHY SUBJECT USING VARIOUS WHOLE-BODY COUNTERS

Total-body potassium (mEq)	Body burden ^{137}Cs(nCi)	Location and type of whole-body counter
4,162	16.4	Argonne National Laboratory, Argonne, Ill. 1 NaI(Tl) 20.3 × 10.2-cm crystal. Chair.
4,700	20.0	University of California, Los Angeles, California. Liquid scintillation. Subject bed.
4,275		Veterans Administration Center, Los Angeles, Calif. 1 NaI(Tl) 20.3 × 10.2-cm crystal. Chair.
4,185	34.6	University of California, Berkeley, California. NaI(Tl) 20.3 × 10.2-cm crystal.
4,230		Boston University School of Medicine, Boston, Mass. 2 NaI(Tl) 20.3 × 10.2-cm crystals. Subject bed.

Mean [counters using NaI(Tl) crystals]: 4,219 mEq.

* Standard error of the mean.

from variations in body build. The first method is direct, and its accuracy is independent of variations in geometry and gamma-ray attenuation in the body. The second method, as pointed out by Moore (*11*), presents geometrical and attenuation problems which can be minimized by using an appropriate geometry.

With a "scanning" geometry, relatively uniform counting sensitivity over the length of the subject is obtained (Fig. 1). There is considerable variation in point-source sensitivity with vertical displacement in an attenuating medium (Fig. 2). However, body potassium is distributed through large volumes of body tissues. Sensitivity increases with phantom thickness for distribution throughout the phantom thickness and decreases with phantom thickness for distribution through 50% of the phantom thickness with this latter "core" centered in the longitudinal midline in the x-y plane. The behavior for planes laterally displaced from the x-y plane can be shown to be similar except that the sensitivity would show an increased tendency to decrease with increasing phantom thickness (Fig. 2).

In the normal subjects studied, the sensitivity of the counter to differences in body build varied by less than 15%. The decrease in sensitivity, as a function of $(W/H)^{1/2}$, is consistent with the results of the phantom measurements if (1) the parameter $(W/H)^{1/2}$ is taken as an approximate index of body thickness and (2) body potassium is assumed to be more centrally distributed with increasing body thickness (Fig. 3). In the first approximation, body build is considered as a cylinder of uniform cross section and constant density. The second approximation assumes that with increasing weight the spatial distribution of body potassium is unchanged and potassium-free surface layers of fatty tissue are added. This results in the potassium distribution occupying a core region which is a smaller fraction of body thickness. Use of the body build index $(W/H)^{1/2}$ derived from the normal subjects (Fig. 4) whose body build varied over a wide range gave results which were in reasonable agreement with the results of ^{42}K calibration. Such results appear to support the second approximation.

It is concluded that body potassium may be readily measured using the "scanning" geometry and a body build index $(W/H)^{1/2}$ without ^{42}K calibration if an error of $\pm 5\%$ (95% confidence limits) is acceptable and if gross changes in the distribution of body potassium are not anticipated. This would apply to screening patients for potassium deficiency or for population surveys or nutritional studies. Differences between replicate measurements of body potassium measurement and metabolic balance in the same subject with potassium depletion and after restoration of body potassium, if significant, may have been due to extrarenal potassium losses. The ^{42}K calibration may only be necessary on one occasion during a prolonged study when either individuals of unusual body build are to be measured or body potassium is markedly altered.

SUMMARY

Body potassium has been determined by measurements of naturally occurring radiopotassium in normal human subjects using a total-body counter. Phantom studies were carried out to demonstrate the effects of variations in body build on ^{40}K measurements using a "scanning" geometry. Use of an index based on body build permits body potassium to be calculated from the ^{40}K counting rate with an error of $\pm 5\%$. More accurate information can be obtained by ^{42}K calibration to correct for effects of body build and potassium distribution on the ^{40}K counting rate.

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