Quality Control Procedures for a Whole-Body Counter*

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Variations in design and laboratory use of a whole-body counting instrument require instrument-specific procedures for quality control and maintenance. The whole-body counter at the Mayo Clinic is a low-level counting facility used primarily for determination of total-body potassium and studies of single isotope retention. Maintenance and quality control procedures of this instrument include: (A) daily controls and efforts to maintain a low and constant background counting rate; (B) monitoring the sensitivity and linear response of the detection system by matching photomultiplier tube response; and (C) performance evaluation, such as evaluation of reproducibility and accuracy of measurements. The procedure for counting total-body potassium in a human subject is described in detail.

Equipment used in the nuclear medicine laboratory is usually the product of a commercial manufacturer. The procedures for operating and maintaining the equipment are published in an operator's manual, and additional information can be obtained from other laboratories using similar instruments. However, whole-body counting instruments represent a different situation in that they are built to various degrees of complexity and cost and each is designed to meet the needs of the specific laboratory, resulting in a variety of designs and laboratory uses. Accordingly, the requirements for operation, maintenance, and quality control differ.

This paper describes the design, operation, maintenance, and quality control procedures of the whole-body counter in the nuclear medicine laboratory of the Mayo Clinic. Description of a method used to evaluate its performance is also included.

Background

A whole-body counter is an instrument that measures the radioactivity in the entire body of a patient and it is usually described in terms of shielding, detector materials, and electronics *(1)*. A flat-field collimated sodium iodide (Tl) crystal probe is a practical whole-body counter when the field of view includes the entire body and the activity level measured provides acceptable counting statistics *(2)*. More elaborate whole-body counting systems use multiple detector arrangements, usually enclosed in a shielded room. The differences in whole-body counters are in the levels of detectable activity, scintillator resolution, geometry of the detector or detectors, complexity, and cost. Due to these differences, the applications to medicine and health physics are limited. As a result, some laboratories have three instruments at the same facility *(3)*.

Description

The inside dimensions of the counting room are 2 meters wide by 2.4 meters high by 2.3 meters deep. Shielding is provided on six sides by 15.3 cm of uncontaminated steel lined with 3.2 mm of lead (Fig. 1). The detector system housed in this room consists of ten plastic scintillators, each 45 x 45 x 15 cm. Six detectors are above the counting cart and four are below it. Each detector has four

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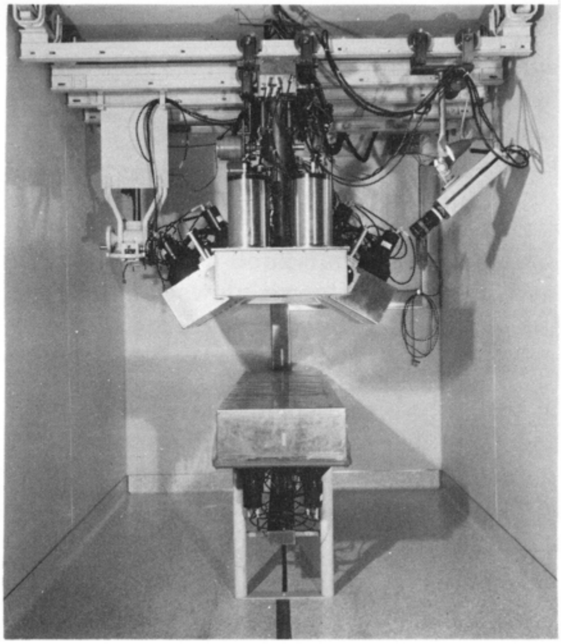

FIG. 1. Whole-body counter in shielded room.

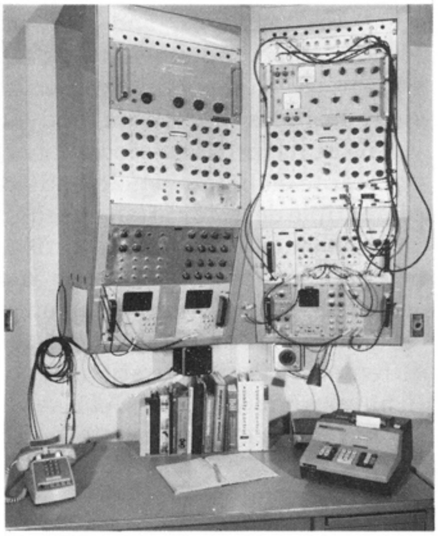

FIG. 2. Control panel for whole-body counter.

photomultiplier tubes. The mechanical support of the upper detectors allows placement to the best source-to-detector configuration. The instrument control panel (Fig. 2) consists of three high-voltage power sources and 40 voltage dividers used to control the high-voltage supply to the photomultipliers, a preamplifier power supply, signal-adding circuit, amplifiers, scalers, and a coincidence module.

Medical Uses

The whole-body counting instrument in our laboratory is used mainly for the determination of total-body potassium in studies of body fluids and electrolytes *(4)*. Total-body potassium is measured by external counting of the 0.0118% naturally occurring ^{40}K. Potassium-40 emits gamma radiation of 1.46 MeV and has a half-life of 1.3×10^9 years. The energy spectrum of ^{40}K in the plastic detector system is different from that seen with a sodium iodide crystal (Fig. 3). For measurement of ^{40}K, a window width corresponding to 1.0 – 2.0 MeV is used. The ^{40}K resolution is 12% as calculated by the half-width at half-maximum method *(5)*. Other uses of the whole-body counter in our laboratory have been studies of retention of microcurie doses of ^{64}Cu, ^{67}Cu, ^{22}Na, ^{47}Ca, ^{59}Fe, and ^{88}Y *(6– 9)*.

The use of whole-body counters in nuclear medicine laboratories has declined in recent years, due in part to the costs involved in maintaining such an instrument and due in part to the fact that retention studies have been replaced as diagnostic tests by simple radioimmunoassay procedures. Besides their importance in research, whole-body counters are needed for monitoring radiation workers, for evaluating radiation accidents, and for measuring naturally occurring ^{40}K. Whole-body counters specifically built for good energy resolution are a necessary part of any in vivo neutron activation analysis laboratory.

Maintenance and Quality Control

In the maintenance and quality control program of a whole-body counting instrument, the level of background and the sensitivity of detection are of prime importance. Due to the low-level activities measured, background counting rates must be maintained at a low and stable level. The primary means of decreasing background is by shielding, usually with uncontaminated steel. It is important that reasonable distances are maintained between radioactive materials and the instrument. Patients who previously had received radioactive materials have been found to be the cause of abnormal

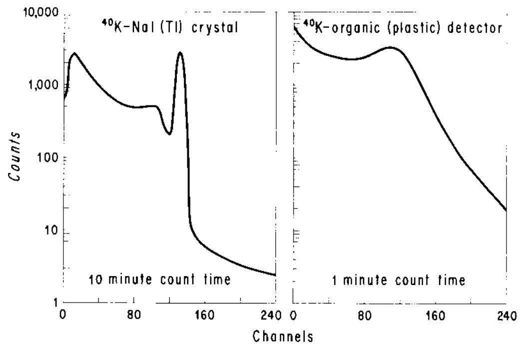

FIG. 3. Comparison of resolution of sodium iodide (Tl) (A) and plastic scintillator (B) systems for ^{40}K.

background measurements in our laboratory, particularly those who had received ^{24}Na, which has a gamma radiation of 2.75 MeV. A precaution we have taken to prevent contamination in our laboratory is the wearing of shoe covers in the room containing the whole-body counting instrument.

Background stability can be affected by the operating levels of electronic components and by the temperature and humidity in the room. We have observed unusual changes of background when ventilation to the counting room has been interrupted overnight. Erratic background measurements also have been traced to electrical noise generated by an electronic calculator; this problem was eliminated by the installation of an interference filter between the line voltage and the calculator. These factors are controllable to some degree. Other factors that affect background measurements and that cannot be controlled with certainty are the level of environmental radiation and the cosmic radiation penetrating the room shielding. Figure 4 shows the monthly means and standard deviations of background measurements in the energy range of 1.0 – 2.0 MeV, with the means ranging from 84 to 98 cps. Although trends of change appear, the operation and maintenance procedures have not, and these trends have not been isolated to the counting system.

The sensitivity of the detection system is maintained by a quality control program of matching photomultiplier tube response and testing the operation of each electronic component. The matching of photomultiplier tubes is done with a 512-channel analyzer with a tape reader input and an oscilloscope display as shown in Fig. 5. The response of one photomultiplier to a ^{60}Co point source at the time the instrument was put into operation has been stored in the form of a punched paper tape. This standard tape is read into the analyzer and stored in 256 channels. The ^{60}Co point source is placed at the center of the detector surface and counted, and these data are stored in the remaining 256 channels of the multichannel analyzer. By oscilloscope display of the two 256-channel spectra, the alignment of the peaks can be observed (Fig. 6). The photomultiplier tube peak is adjusted to match the standard peak by using the high-voltage control to the photomultiplier. Once matched, the 256 channels storing the test peak can be erased. This process is repeated for each photomultiplier tube.

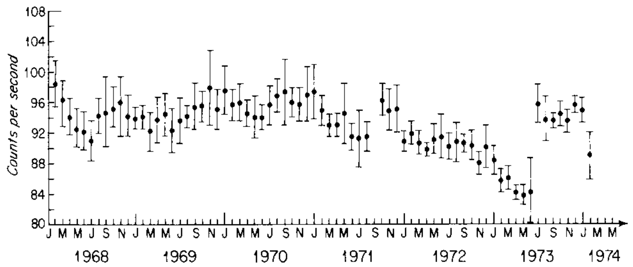

FIG. 4. Mayo Clinic whole-body counter background measurements in range of 1.0–2.0 MeV, as monthly mean ± s. d.

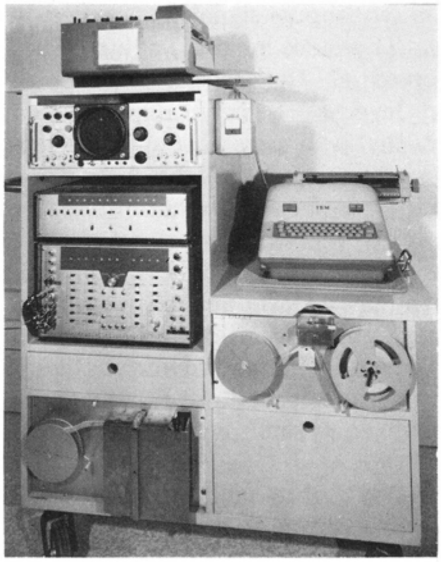

FIG. 5. Multichannel analyzer system used in quality control procedures.

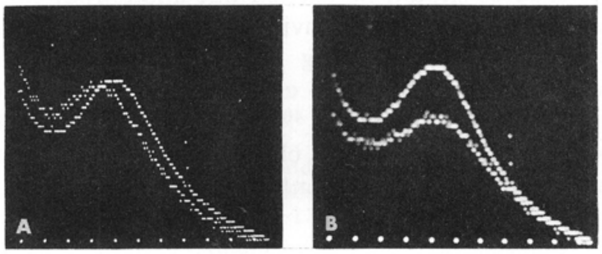

FIG. 6. Multichannel analyzer oscilloscope display of ^{60}Co spectra demonstrating misalignment (A) and alignment (B).

When all 40 photomultipliers have been matched, the ^{60}Co source is removed from the counting room, and a source of ^{40}K (23 kg of KCl) is placed in the counting room. The signal of all detectors in response to the ^{40}K source is the input to the multichannel analyzer and is stored in 256 channels. A standard tape of the same ^{40}K source (recorded at the reference date) is stored in the remaining 256 channels. The spectra are compared, and matching is done by adjustment of the amplifier system.

The operating characteristics of each electronic component can be monitored by applying an internally generated signal to the input of the device. The internal signal is generated by a system that allows adjustment of pulse height, polarity, rise time, and dead time. With the high-voltage supply of each photomultiplier off and the scaler clock on, an input signal is applied to a preamplifier. The pulse height is adjusted until counts are observed at the scaler; this represents the threshold level of a signal, applied at the preamplifier, that will pass through the low level of the single-channel pulse-height analyzer. The pulse height is increased until the counting rate begins to decrease; this represents the cutoff level of the signal, applied to the preamplifier, that will pass through the upper level of the single-channel pulse-height analyzer. Both levels of pulse height are recorded with the characteristics of the signal. This procedure is then carried out for the amplifiers and pulse-height analyzers by applying the signal to each input.

The records obtained from this testing can isolate improper performance of an individual component or can indicate shifts within the normal operating limits. Our experience suggests that, unless erratic performance is suspected, these procedures should be carried out about four times per year. The sensitivity of our whole-body counting system during the past 5½ years has ranged from 297 to 316 cps in the energy range of 1.0 – 2.0 MeV from a ^{40}K standard (850 gm of potassium as potassium chloride in triple-distilled water in polyethylene containers) (Fig. 7).

Reproducibility

To evaluate the performance of the whole-body counter, we chose the reproducibility of measuring total-body potassium (TBK). The results of a recent study of reproducibility of the measurement in five subjects are shown in Table 1. The mean coefficient of variation was 3.5%. These data also were analyzed for within-day and day-to-day variation and no differences were found.

Another study of reproducibility of measuring TBK was made on data collected over several years.

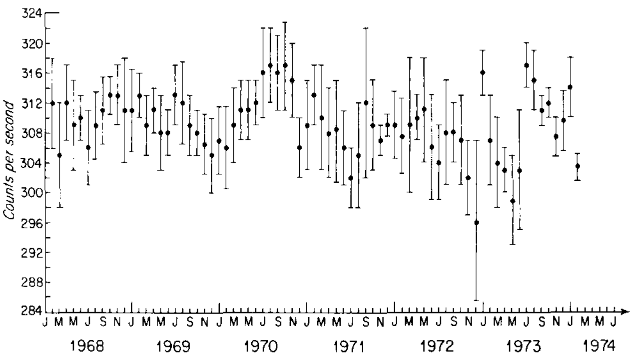

FIG. 7. Counting rate with 850-gm potassium phantom in Mayo Clinic whole-body counter; range, 1.0 – 2.0 MeV; monthly mean ± s. d.

TABLE 1. Reproducibility of Total-Body Potassium Measurement

Subject	Total potassium (meq) Mean	s.d.	Range	Coefficient of variation %
1	2,627	113	2,448–2,818	4.3
2	2,807	142	2,625–3,073	5.1
3	4,645	91	4,510–4,769	2.0
4	2,591	82	2,466–2,733	3.2
5	3,682	114	3,492–3,825	3.1

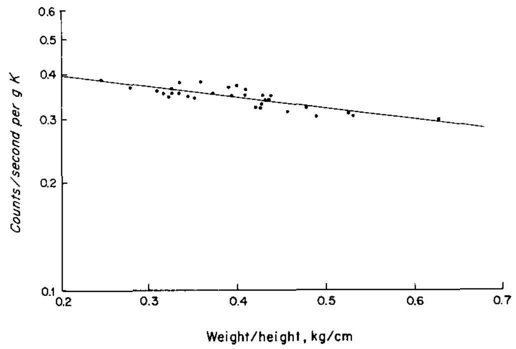

FIG. 8. Calibration curve to correct for differences in human shape and size. Data are from 32 normal subjects who were given known amounts of ^{42}K and then counted under standardized conditions as described. The line is described by: $\log_e$ cps/gm K = –0.6883 (wt/ht) – 0.7965 (r = –0.822).

All subjects were employees and were measured on a monthly basis. Among these 17 subjects, the number of measurements on each subject ranged from 6 to 26. The average coefficient of variation in this group was 3.2% (range, 1.5– 5.2%).

The reproducibility of the TBK measurement in human volunteers includes uncontrolled sources of variation due to changes in the body potassium stores. To compare the human data to data from a constant potassium source, a phantom containing rice was constructed to form a "subject" 169 cm long and weighing 66.8 kg. Analysis of the rice for potassium by ashing and flame photometry showed it to contain 39.4 meq/kg, a level near that expected in normal women. The actual TBK of this "subject" was therefore 2,632 meq. For 61 measurements of this "subject" over a span of 4 months, the mean ± s.d. was 2,565 ± 77 meq. The coefficient of variation for this "subject" was 3.0%, comparable to that found in the human subjects.

Example of TBK Measurement

Counting of subject. Two 300-sec counts are obtained with the subject lying on a counting cart in the counting chamber. Pulse-height analyzers are set to a window of 1.0– 2.0 MeV.

TABLE 2. Measurements in Adult Subject

Measurement	Value
Background (70 kg sugar)	85.00 cps
Subject	137.12 cps
Background (70 kg sugar)	84.00 cps
Average background	84.50 cps
Subject net counts	52.62 cps
^{40}K adult phantom (850 gm K)	385.96 cps
^{40}K adult phantom net counts	301.46 cps
Subject height	175 cm
Subject weight	70.0 kg
Weight/height ratio*	0.400

**Weight/height ratio of 0.400 corresponds to a counting efficiency of 0.343 cps/gm potassium as obtained from a counting efficiency table prepared in our laboratory.*

TABLE 3. Calculations on Measurements of Adult Subject (from Table 2)

$$\text{Subject TBK} = \text{subject net cps}\left(\frac{\text{counter efficiency}}{\text{subject counting efficiency}}\right)$$

$$\text{Counter efficiency} = \frac{\text{reference counting efficiency}}{\text{adult phantom (net counts)/850}} =$$

$$\frac{0.3619}{301.46/850} = 1.0204$$

Subject counting efficiency = 0.343 cps/gm K (at a wt/ht ratio of 0.400)

$$\text{Subject TBK} = 52.62\text{ cps}\left(\frac{1.0204}{0.343\text{ cps/gm K}}\right) = 156.5\text{ gm K}$$

$$\text{Conversion of gm into meq} = \frac{\text{K (gm)} \times 1{,}000 \times \text{valence}}{\text{atomic wt of K}} =$$

$$\frac{156.5\text{ gm} \times 1{,}000 \times 1}{39.1} = 4{,}002\text{ meq}$$

Background. The subject is replaced on the counting cart by several plastic containers filled with 70 kg of cane sugar. Sugar, which is free of potassium, is selected to simulate the effect of a potassium-free human body on the background counting rate in the counting chamber. An empty-room background counting rate is higher by approximately 2 cps.

Counting efficiency. An arrangement of polyethylene containers filled with 850 gm of potassium dissolved in triple-distilled water is counted. The result is expressed as counts per second per gram of potassium. The value obtained in our counter for this phantom was 0.3619 cps/gm potassium during counter standardization and is referred to as reference counting efficiency. Daily variations from this value are considered in the calculations under "counter efficiency."

Calibration and calculations. It is necessary to correct for variations in source-to-detector geometry due to differences in shape of the human body. The adopted method is to count a phantom corresponding to the mean length and weight of age-matched normals. The value of this procedure was established in experiments using human volunteers who were given different doses of ^{42}K (Fig. 8). The measurements in a typical adult subject are shown in Table 2 and calculations are given in Table 3.

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