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A ROTATIONAL TECHNIQUE FOR ASSESSING QUANTITY AND DISTRIBUTION OF BODY RADIOACTIVITY

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Abstract—A new whole-body counter is described that provides a method for the determination of the amount and distribution of radionuclides in the human body. The quantitative measurements are relatively independent of differences in the distribution of the radioactivity in the body or the anatomical differences of the individuals who receive the whole-body counts. The measurement is taken with the human subject rotating on a power-driven turntable while the scintillation detectors move down the longitudinal axis of the rotating body. The result of rotating the body with respect to the detector is the elimination of effects caused by changes in location of the radioactivity and the differences in the absorption; essentially the effects of these factors are averaged. Because sources of activity that are displaced from the axis of rotation in a revolving sample or human body produce oscillations in counting rate, the approximate location of the radionuclide can be determined at the time of the quantitative measurement. The position of the detector with respect to the different parts of the body can be defined as a point along an imaginary helix if the measurement is taken while the detector is moving down the longitudinal axis of the rotating body. The location of the radioactive source is indicated by increased counting rate at points along this helix which surrounds the body. Counting rate, linear distance of the detector down the body from a reference point, and body orientation with respect to the detector are the three variables for defining the position of activity. This technique of counting is especially applicable for the *in vivo* determination of radionuclides in the human subjects because both the body radioactivity and approximate distribution can be determined simultaneously. In addition to whole-body counting, the combined rotation and scan technique is also a method for the determination of activity in biological samples in which large volumes are required to obtain adequate sensitivity. The procedure can be used for any type of solid samples that contain an unknown distribution of activity. The density of the matrix material in which the activity is contained and the distribution of the activity in the sample are discussed as factors affecting absolute counting.

Applicability of the method to *in vivo* whole-body counting has been confirmed by counting ^{131}I and ^{54}Mn at various locations inside a human volunteer. The maximum variation of counting rate for different positionings of the sources in the body was 400 and 19 per cent for the static counting method and the new rotation method, respectively. The counting sensitivity is comparable for the two methods if the volumes of scintillation detectors are equal.

RADIONUCLIDES can be determined quantitatively by gamma spectrometry, but the energies must be sufficiently different to permit resolution of the different components of the spectrum, and a known counting geometry must be maintained. Both the distribution of the activity in a sample and the matrix which surrounds the source of activity must be known. Solid samples are first dissolved and treated to remove absorber materials which are present in unknown amounts, then mounted in some uniform configuration for counting. These necessary steps for preparation of the sample are obviously impossible when *in vivo* determinations are required to measure radionuclides in human subjects. Both the configuration of the sample and density of the matrix containing the source of activity are variable; and the distribution of the activity is generally not known.

Errors due to counting geometry can be

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maintained by positioning the body a relatively long distance from the detector if high sensitivity is not required. However, the amount of absorber and the density of the absorber between the points of activity in the body and the scintillation detector are still not altered by this increased distance. These variables continue to be a source of error. Considerable work has been done to determine optimum positioning of the body with respect to the scintillation detectors for whole-body counting. The tilting-chair and the 50-cm-arc techniques are two of the more common methods,[1-3] and, more recently, whole-body counters have been developed with multiple-crystal arrays as detectors.[4] The shadow-shield counter has a single detector, but the body is scanned during the period of counting.[5] When detailed energy resolution is not required, liquid scintillation whole-body counting is the preferred method.[6] Differences in the distribution pattern of the activity in the body have less effect on the counting rate under these conditions of counting, but the method is essentially for the determination of gross gamma activity.

The purpose of this investigation is (1) to show how the position of a radioactive source in a sample affects counting rate when the sample is maintained in a state of rotational motion, (2) to show this effect again with simultaneous rotation and scanning of the sample, and (3) to show the application of this combined rotation and scanning method of counting for assessing the quantity and distribution of the radioactivity in the body. Whole-body counting by this method is referred to as the rota-scan technique, and the method for the determination of the position of the source in the body is designated as helical scanning.

EXPERIMENTAL

The experimental apparatus consisted of a gamma spectrometer, recording counting-rate meter, and the necessary equipment for rotating either the experimental models of samples or human subjects during the process of counting (Fig. 1). The detectors were moved along the body or sample by a motor-driven carriage, and a revolving turntable provided the rotational motion. The output from the two 8- by 4-in. NaI(Tl) detectors was stored in separate halves of the memory of a 400-channel analyzer

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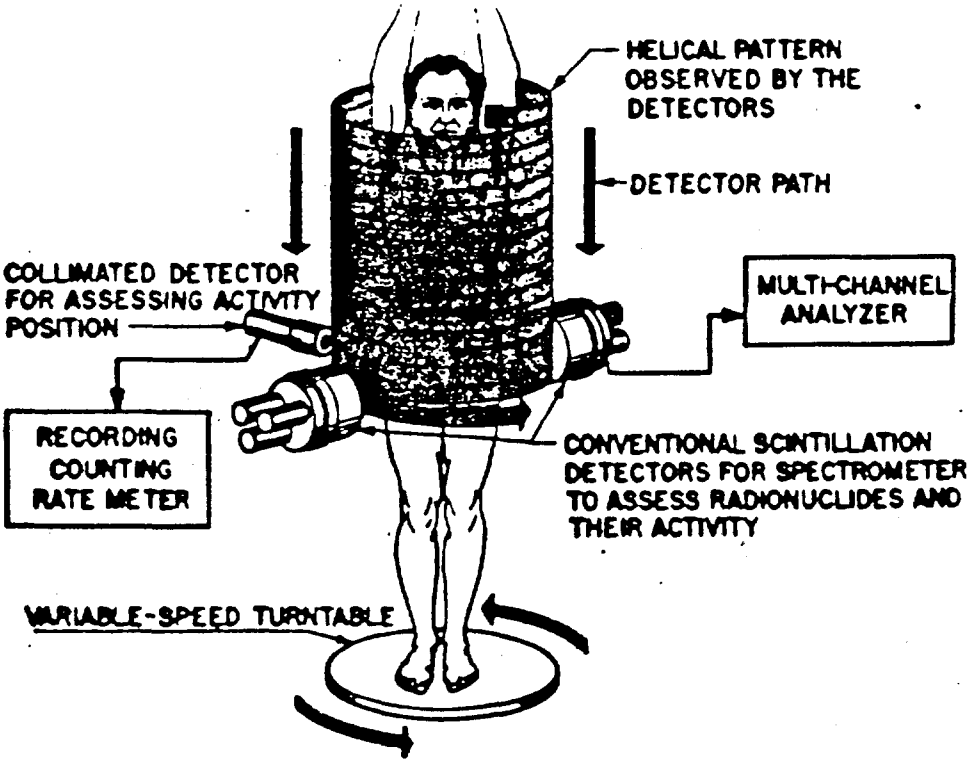

FIG. 1. Diagram of experimental rota-scan counter.

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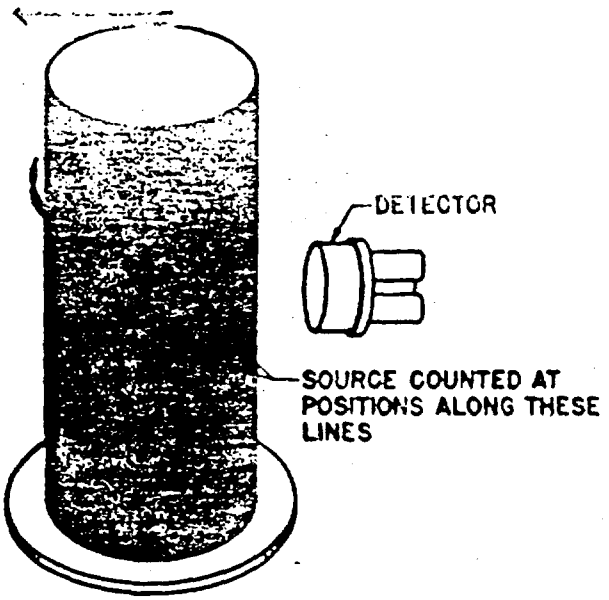

FIG. 2. Experimental sample model used to compare the effect of source position on counting rate for static counting and rotational or rota-scan counting.

from which the gamma-energy spectra were available from readout by typewriter, paper tape punch, or an X–Y plotter. A counting-rate meter with an X–Y plotter was operated from the output of a 3- by 3-in. collimated detector or from one of the 8- by 4-in. whole-body counting detectors to obtain the helical scan plots. The experimental models of samples that were used to demonstrate the effect of rotation consisted of liquid-tight cylindrical containers with provisions for mounting the source at selected positions (Fig. 2).

The effect of the distance of the source from the detector and the effect of changes of the matrix for rotating samples were determined by repeated counting of sources in different absorbers at selected positions in the sample. Air, water, and tissue-simulant solution were the different matrices surrounding the sources of activity that were suspended at positions along a small wire extending through the center of the cylindrical sample. To determine the effect of position of the activity on counting rate, large samples approximating the size of the human body were counted repeatedly by the method of simultaneous rotation and scanning (rota-scan technique) with radioactive sources at different locations in a water matrix.

A life-size manikin with accurately positioned organs was used to simulate the human body for the collection of the first helical scanning data. The position of radioactive sources placed in selected organs was determined by moving the detector at a constant rate, lengthwise, along the rotating body. Counting rates were recorded by an X–Y plotter as a function of detector position (down the longitudinal axis of the body) and the orientation of the body. The latter two variables define the detector position along an imaginary helix surrounding the body. Helical scans were taken with sources in the lungs, stomach, and kidneys; and both the body rotation rate and the detectors were changed for different trials. Finally, human subjects that had voluntarily ingested radionuclides were repeatedly whole-body counted at different times after exposure by the rota-scan technique and the conventional method (50-cm-arc). Both the rota-scan whole-body spectrum and a helical-scan plot were obtained simultaneously as a part of the experimentation.

RESULTS AND DISCUSSION

The effect of rotating the sample during the process of counting

Figure 3 shows a comparison of counting rates for different positions of a source inside a rotating sample and a sample counted in a static state. Data points are from integrated counts under the 0.66-MeV photopeak of ^{137}Cs measured as a point source suspended in water. Spectra were obtained with the source at different positions along a line extending from the sample center in a direction 90° to the axis of rotation. The crystal face was also in a plane 90° to the source positioning line for the case of static counting. The axis position is shown on the graph as zero distance at the center of the abscissa, and the two halves of the curve for the rotation data are duplicates to the right and left of zero (Curve 2 of Fig. 3). The lower scale is the source distance from the 8- by 4-in. crystal face. These numbers refer to the curve for the sample which was counted without rotation. A plot of this data is shown for the purpose of comparing the two methods

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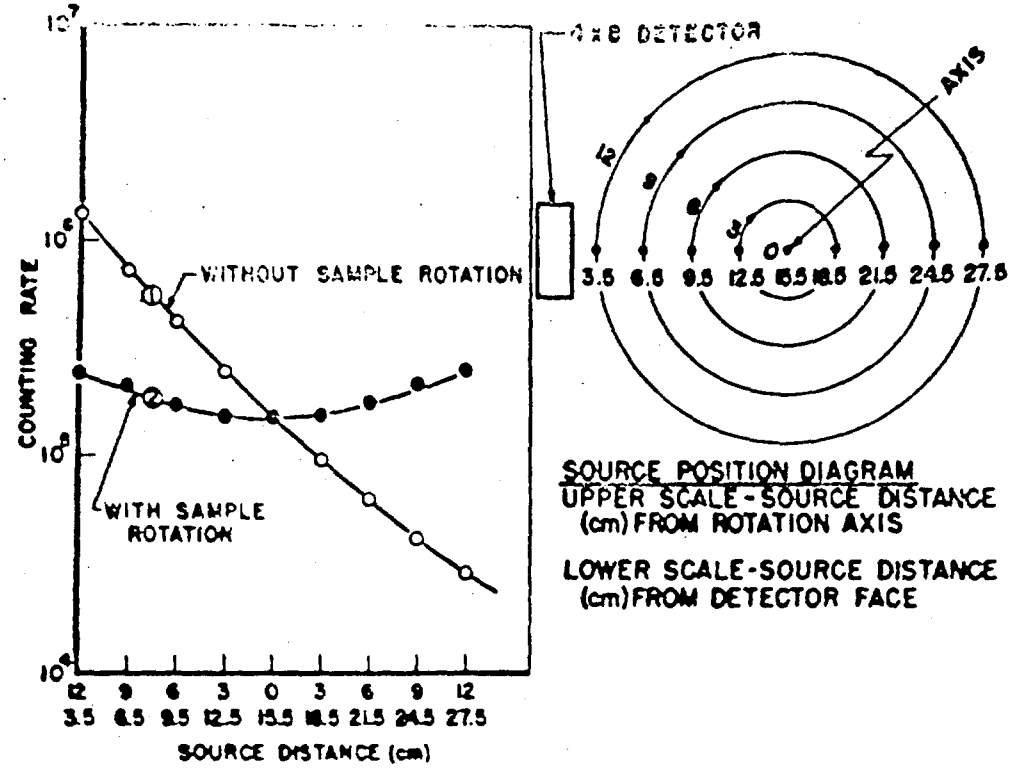

FIG. 3. Effect of source position change on counting rate with and without sample rotation-source in water.

Curve 1. Static counting with source displacement at 90° to the crystal face.

Curve 2. Sample rotation counting using the same source positioning.

of counting. The counting rate for the rotating model increased as the source distance from the axis became greater. The difference with the source positioned at the axis of rotation or at 12 cm from this point is approximately 33 per cent which is a distance change from a minimum of 3.5 cm from the crystal face to a maximum of 27.5 cm from this reference point. The difference was about 400 per cent with the source at these same two positions when the sample was counted in a static state (without rotation) as shown by Curve 1 of Fig. 3.

The effect of the matrix surrounding a source of activity in a rotating sample

Tissue simulant solution is compared with air as the medium surrounding a point source of ^{137}Cs counted at different positions inside a rotating sample (Fig. 4). The maximum displacement of the source from the rotation axis was 5.7 cm, and the minimum and maximum distances from the detector face were 2.8 cm and 14.8 cm, respectively. All four curves represent data for identical conditions of counting except for the change of the absorber or matrix surrounding the radioactive source. Curves 1 and 2 of Fig. 4 are based on gross gamma counts, summation over the complete energy range of ^{137}Cs; Curves 3 and 4 of Fig. 4 are from the same spectra, but the data points represent integrated counts under the 0.66 MeV photo-peak. Increased variation of the counting rate is indicated with the higher density absorber surrounding the source when counts under the photo-peak only are the basis of counting rate, which is evident from a comparison of Curves 3 and 4 of Fig. 4. The absorber had the opposite effect, causing the counting-rate variability to decrease for differences in source position when gross counting was the basis for counting rate, shown this time by the comparison of Curves 1 and 2 of Fig. 4. When air was the only medium surrounding the rotating source, the position of the source had the same effect on the counting rate for either gross counts summed over the complete energy range of the

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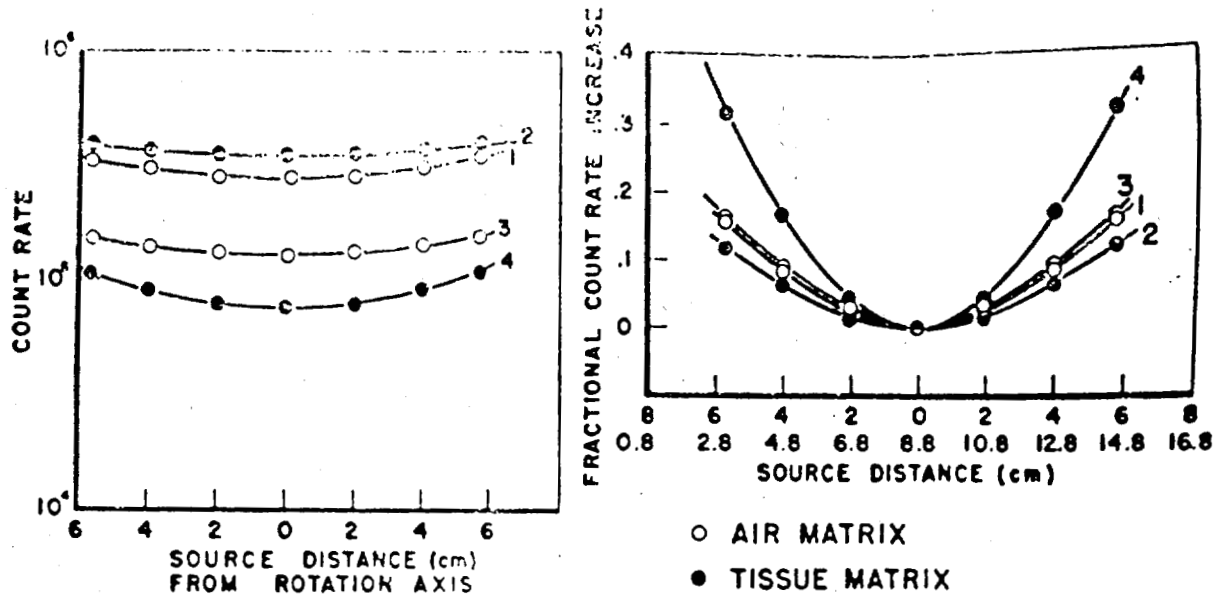

FIG. 4. Effect of source matrix on counting rate for rotating samples.
Curve 1. Air matrix—gross counting.
Curve 2. Tissue simulant matrix—gross counting.
Curve 3. Air matrix—peak integral counting.
Curve 4. Tissue simulant matrix—peak integral counting.

spectrum or for the integrated counts under the photo peak (Curves 1 and 3 of Fig. 4). The fractional differences for the counting rates are plotted as a function of source position, shown by the graph at the right in Fig. 4.

Counting of large samples by combined scanning and rotation (rota-scan)

Results of rota-scan counting of large samples, approximating the size of the human body, are shown in Fig. 5. The two curves show results of counting a source of ^{137}Cs, suspended in water, at different positions on a line extending diagonally through a 30- by 92-cm cylindrical container. A diagonal distance of zero, as indicated by the diagram to the right, is designated as the position of the source which is the greatest distance from the detector with the cylinder in the position for static counting. Counting with neither sample rotation nor

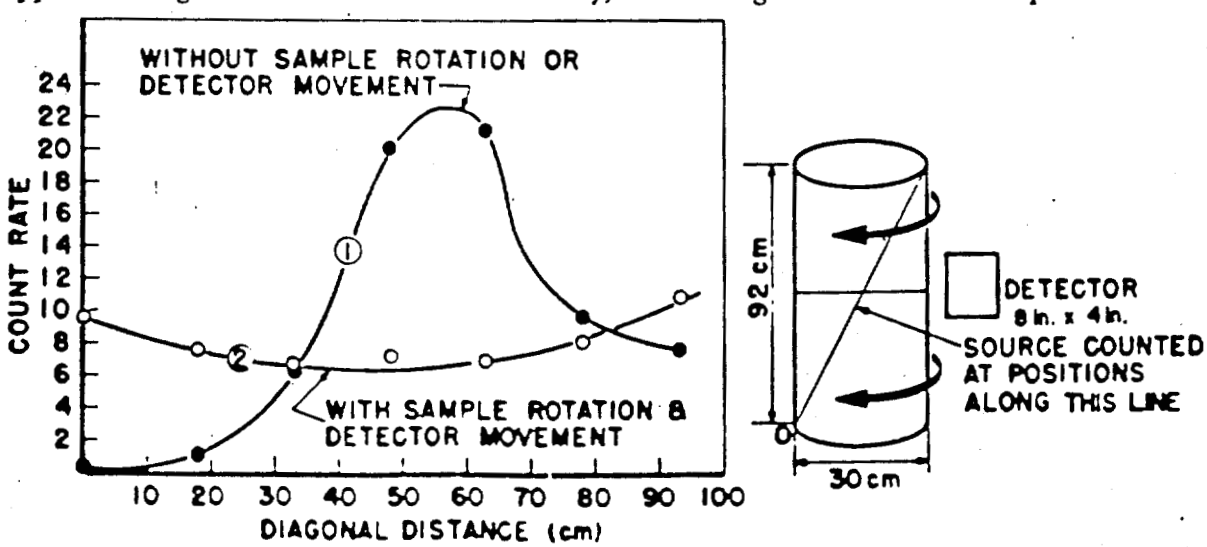

FIG. 5. Effect of combined rotation and detector movement along the sample.

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detector movement was done with the detector remaining at a position over the center of the cylinder. The data for Curve 2 of Fig. 5 were obtained with the cylindrical container rotating at 2.4 rpm while the detector moved 7.6 in./min parallel to the axis of rotation. The outside edge of the detector was aligned with the end of the container at both the time of the beginning and the time of the termination of the scan. Each point on the curve is for a different position of the source along the diagonal line indicated in the diagram. The counting rate shows an increase as the source was displaced from the rotation axis toward the end of the cylinder. However, this variability in counting rate from results of rota-scan counting is not excessive when compared to the data obtained with the sample remaining static during the period of counting.

Rota-scan as a method of whole-body counting

A comparison of the conventional method (static counting) and the rota-scan technique for whole-body counting of a human subject is shown in Fig. 6. For the first phase of the study, the data were from repeated counting of an individual who had ingested ^{131}I (Curves 1 and 2 of Fig. 6). The activity was sealed in a three-layer gelatin capsule and taken orally immediately before the first whole-body count. Initially the activity was a point source; but after dissolution, the radionuclide was subjected to the characteristic metabolic processes for iodine in the body. During the 24-hr time interval, changes in position of the activity resulted so that distribution differences are also represented by points along the abscissa. Variations in counting rate show the inability of the indicated technique to compensate for distribution changes of the radionuclide in the body. The state of the activity ranged from a point source, initially, to a widely distributed source then back again to a point source as part of the ^{131}I became concentrated in the thyroid. All whole-body counting data were corrected for radiological decay and excreted activity, and the counts recorded were from the 0.36-MeV photopeak of ^{131}I integrated over the energy range from 0.31 MeV to 0.44 MeV. Compton contribution from the peaks above 0.36 MeV was subtracted. The first whole-body count was 0.8 hr after the capsule had been taken orally into the body and is represented as the high point on Curve 1 of Fig. 6. This count was before the first indication of activity in the blood. The capsule dissolved, releasing iodine to the blood stream, sometime during the time interval from 2.0 to 3.5 hr. This information was from the hand counting data. Maximum activity in the blood was at 4.7 hr after the capsule was ingested, which is also the time the low point appears on this curve from the static counting data. The activity was undoubtedly dispersed to the greatest extent throughout the body at this time. The iodine in the blood, circulating in

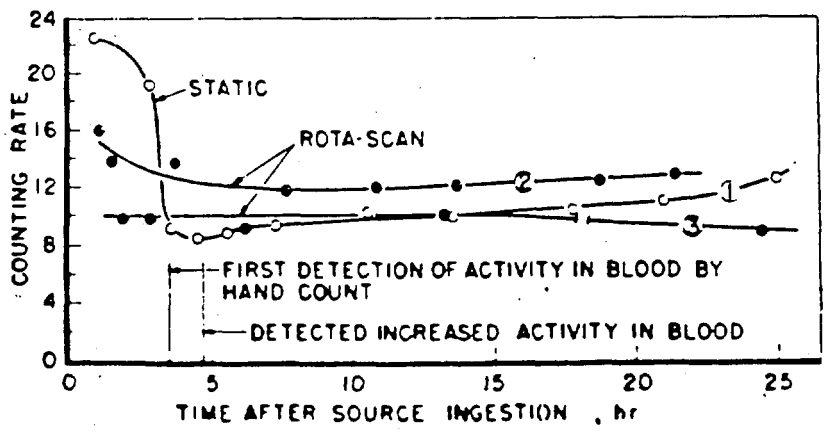

FIG. 6. Comparison of static and rota-scan techniques of whole-body counting.
○ ⊕ Soluble capsule of iodine-131 counted in vivo by the two different methods.
● Insoluble capsule containing iodine-131 counted in vivo by rota-scan technique.

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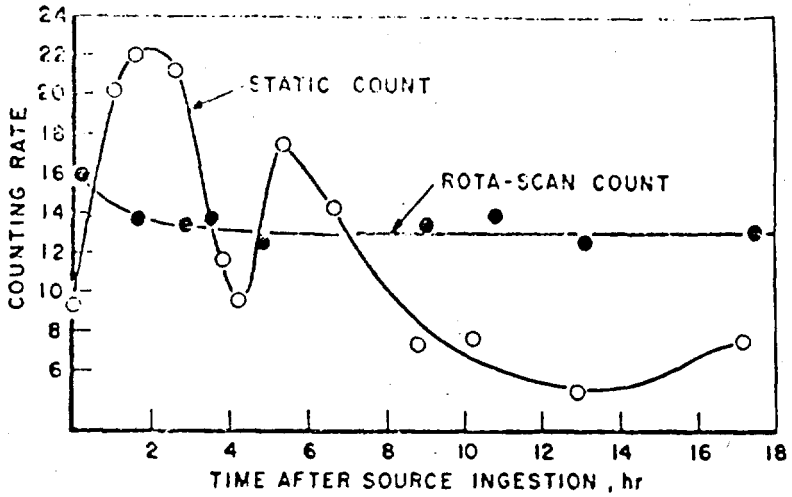

FIG. 7. Comparison of static and rota-scan techniques for whole-body counting of a human subject with an insoluble source of manganese-54 at various locations along the GI tract.

the legs, head, and other extremities of the body, would contribute very little to the counting rate. The gradual upward slope of the curve between 5 and 25 hr could result from the slow transfer of this activity from the blood stream to the organs of the body that were relatively near the detector, with less absorber between the source and the scintillation crystal. The iodine would be concentrated in the thyroid, liver, and bone after equilibrium had been reached.[7]

The results of whole-body counting by the rota-scan technique are shown by Curve 2 of Fig. 6. The data points for this curve were from repeated counting of the same individual who had been exposed to the soluble ^{131}I and were used to obtain the previously discussed data from whole-body counting by the conventional technique. The initial counting rates which were obtained before dissolution and blood uptake, were high; but the variation was much less for this method of counting. This downward curvature of the plot, covering the interval up to approximately 5 hr, could result from the combination of events indicated above. The sequence of events could include the dissolving of the capsule, traveling of the released activity further down the gastrointestinal tract, and the transferring of the activity into the blood stream. The difference in the counting rate at 1 and 8 hr is probably the result of a change from a point source to a widely distributed source, which undoubtedly represents the most adverse conditions of source distribution changes that would be encountered in whole-body counting. After release of the iodine to the blood, the curve slopes slightly upward as the activity becomes concentrated in the organs. The small difference in counting rate for this large difference in geometry is insignificant, especially when compared to the results of static counting. Results of another study show the counting rate remained nearly constant for an insoluble point source at different positions along the gastrointestinal tract (Curve 3 of Fig. 6). Those results again demonstrate the capability of the rota-scan technique to reproduce counting rates for large differences in the position of the activity in the body. The curve shows a slight downward slope as the source moved to a position in the rectum near the terminal point of the scan. The data for the 25-hr point were obtained immediately before elimination of the capsule in the feces.

Figure 7 shows a comparison of static and rota-scan whole-body counting for measuring activity of an insoluble capsule of ^{54}Mn at different positions along the gastrointestinal tract. The counting data were from integrated counts under the 0.84 photopeak of ^{54}Mn. A high counting rate was observed for the rota-scan method immediately after the source entered the stomach, but the curve is parallel to the abscissa for all measurements after the

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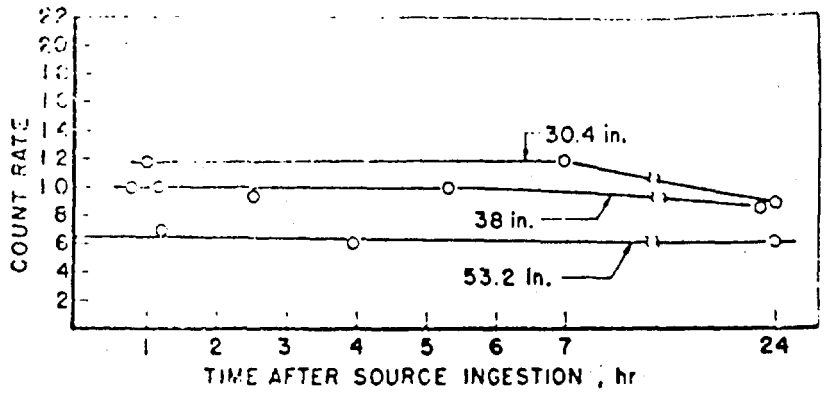

EFFECT OF SCAN LENGTH

FIG. 8. Rota-scan method applied to whole-body counting.

source had been in the body more than 2 hr. Maximum and minimum counting rates for the static counting method were taken at 1.5 and 13 hr, with the source positioned in the stomach and lower colon for the high and low points on the curve. These source positions were determined by helical scanning of the body at the time of the whole-body count. The additional high point on the curve, at 5.3 hr, resulted from a source positioned in the small intestine, toward the ventral side of the body in line with the center of the detector. Other low points on the curve were obtained with the source in the lower large intestine. The reason for the low count at zero time is unknown. However, the source may have been positioned in the lower end of the esophagus or along the posterior wall of the stomach at a greater distance from the static detector. The capsule was swallowed with the subject in the counting position.

The effect of the scan length for stabilizing the counting rate caused by differences in activity position was investigated by counting an insoluble source of radioactivity at different positions along the intestinal tract. Although the amount of data collected was limited, the importance of this variable is demonstrated in Fig. 8. The decreased counting rate at approximately 24 hr is the result of the increase in the amount of absorbers surrounding the source at this point in the lower gastrointestinal tract, added to the effect of positioning of the activity nearer the terminal point of the scan. Extension of the scan length was effective in compensating for this deviation from linearity. Results of this study demonstrate the importance of determining optimum scan length and the points along the body for the start and termination of the scan.

Helical scanning

Helical scanning was investigated as a technique to determine the location of activity in the body. Figure 9 shows the variation in the instrument response from activity in a human-size manikin which was maintained in a state of rotational motion with the detector moving lengthwise along the body during the period of counting. The detector position on the longitudinal axis of the body (scale at the center of the graph) is plotted as a function of counting rate. Body orientation with respect to the detector is indicated along the top of the figure. With the manikin facing the detector, the orientation of the body is defined as zero degrees. The point on the symbols indicate the direction that the body is facing (nose position) with respect to the detector symbols below. The anatomical drawing shows the position of the body organs with respect to the peaks of the counting rate meter response curves. Sources were positioned in the kidney and lung to obtain the data for this first helical scan. The body was rotated at 0.6 rpm and the 8- by 4-in. detector (without collimation) moved along the body at 2.2 in./min. Peaks are visible each time either the kidney or lung, which contained the source, was a minimum distance from the detector. The peaks resulting from

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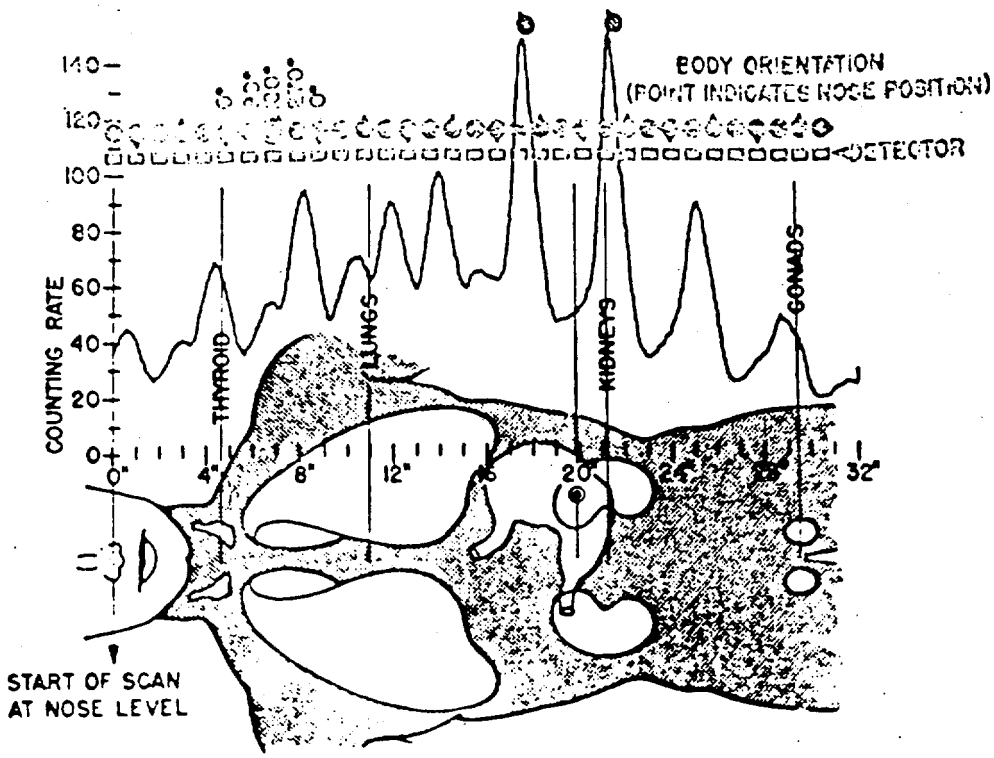

FIG. 9. Helical scan using "Remcal" manikin, 8 in. × 4 in. detector without collimation, sources in lung and kidney.

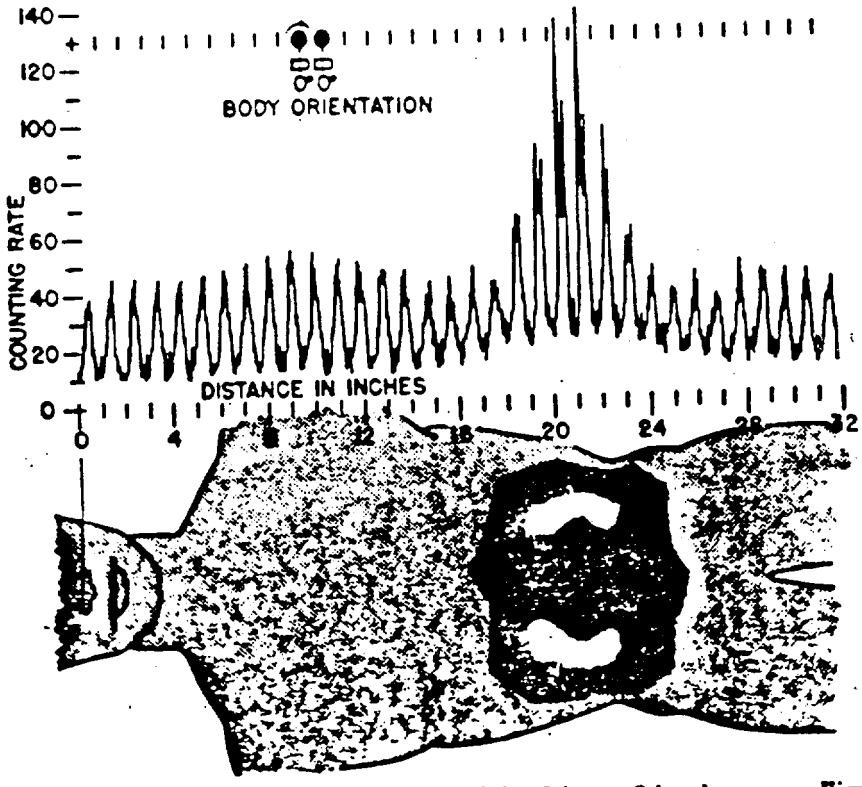

FIG. 10. Helical scan using "Remcal" manikin, 3 in. × 3 in. detector collimated to 1.0 in., source in each kidney.

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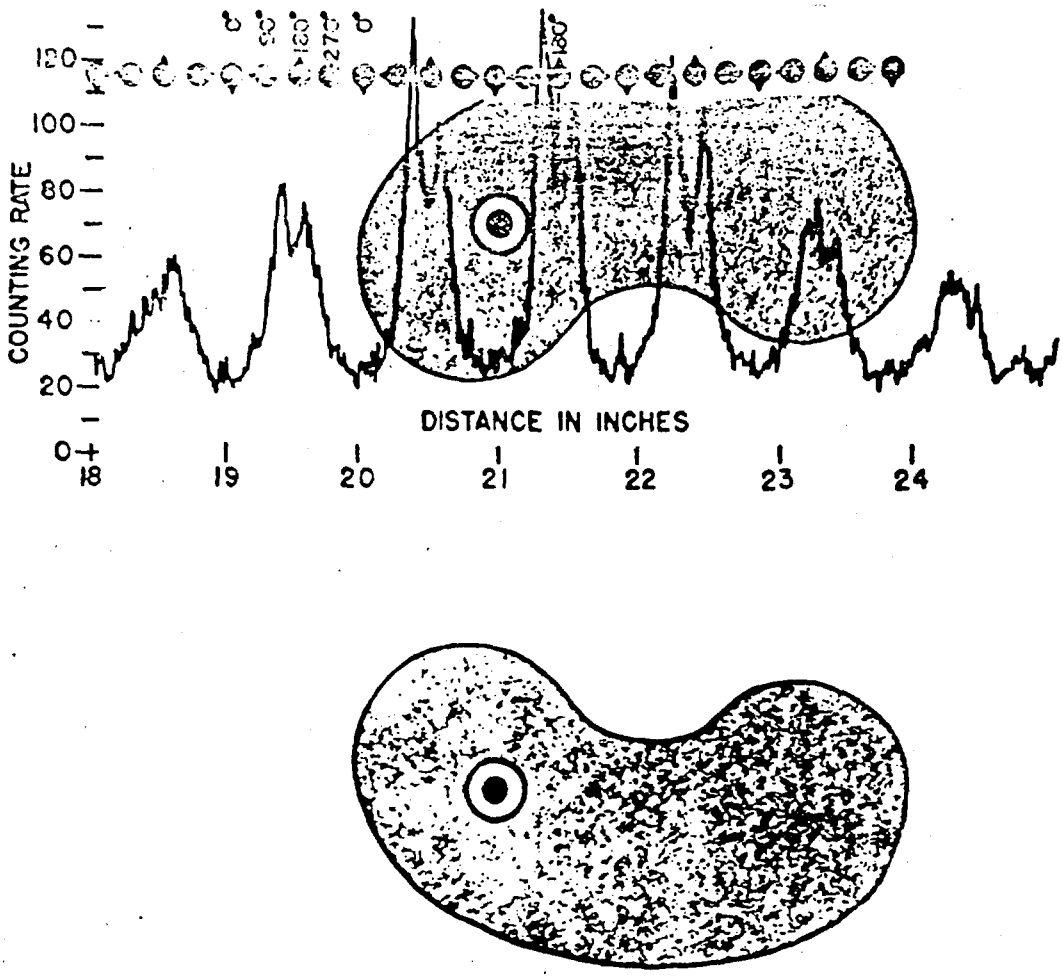

FIG. 10A. Helical scan-sources in kidneys of "Remcal" manikin.

lung activity predominate until the detector was at a position greater than 12 in. down the body from the point of the nose. The high peak from lung contribution was at 8 in., occurring at a point over the upper half of the lung. The body orientation indicated for this high counting rate shows the right side of the body toward the detector (~300°). The counting rate contribution from the kidney predominates at distances greater than 12 in. along the body, with peaks of equal height occurring at 17.5 and 21.5 in. The peaks from kidney contribution occur repeatedly with the indicated body orientation at about 135°. The high peaks resulted when the detector was over the left kidney.

A collimated detector was effective for resolving sources positioned in each kidney of the manikin (Figs. 10 and 10A). The upper curve was obtained with a 3- by 3-in. scintillation detector collimated to 1 in. The scan rate was maintained at 2.2 in./min, but the body rotation rate was increased to 2.4 rpm. Two peaks are resolved for a single turn of the body, and the high peak of the curve is at 21 in. which is directly in line with the kidney position. The curve shown in Fig. 10A is the scan for the kidney area only and is between 18 and 24 in. The abscissa scale was expanded to obtain the detail curve. The two well-resolved peaks occur 90° apart, with the valley between the peaks at 180°. For this orientation of the body, the position of the detector is at the center of the back, between the two kidneys. Relative activity levels for the two kidneys are indicated by peak height differences.

The investigation of the helical scanning

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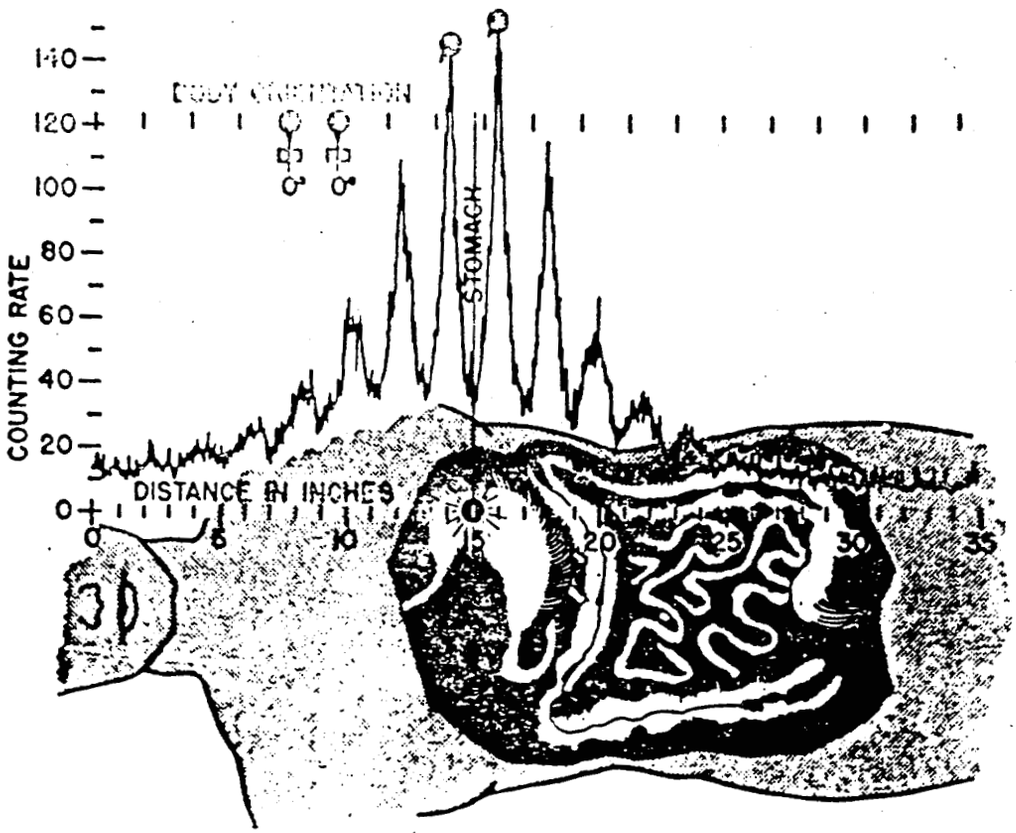

FIG. 11. Helical scan of human body. Point source of manganese-54 in stomach. 3 in. × 3 in. detector with 3 in. collimator. Scanning rate 2.2 in./min. Body rotation rate 1.2 rpm.

technique was extended to *in vivo* determinations of the position of activity in a human subject. Scans were obtained of an individual who had voluntarily ingested a radioactive source containing 1 μCi of insoluble ^{54}Mn. Twelve different observations were made at intervals over a 20-hr period to determine the different positions of the source along the gastrointestinal tract. The rate of movement of the detector down the body was 2.2 in./min, and the rotation rate was maintained at 1.2 rpm. The 3- by 3-in. detector was collimated to 3 in. Detector movement, at a rate of 2.5 in./rev of the body, gave a slight overlap of the helical pattern to ensure complete coverage of the body surface.

The first scan of the individual was at 0.2 hr after ingestion of the insoluble capsule of ^{54}Mn (Fig. 11). A maximum counting rate is indicated with the detector at a distance of 15 in. down the body from the point of the nose. The peaks occur with a body orientation of 65° with respect to the detector (body facing toward the right from the detector axis) and show that the source was displaced from the body axis toward the left side. The source position as indicated by the experimental data is shown on the anatomical drawing. This position in the stomach agrees with the postulate location at 0.2 hr after ingestion. At 5.5 hr after ingestion, the source had moved to a position 25 in. down the body (Fig. 12). The orientation of the body (shown by the scale and symbols at the top of the graph) was 30°, with the detector receiving maximum signal at the time the body was facing slightly right from the detector axis. These experimental results place the source, as indicated by the drawing, at a point in the small intestine which was toward the ventral side of the body. The helical scan, taken at 13.1 hr after ingestion of the activity, indicates a source position 19 in. down the body from the

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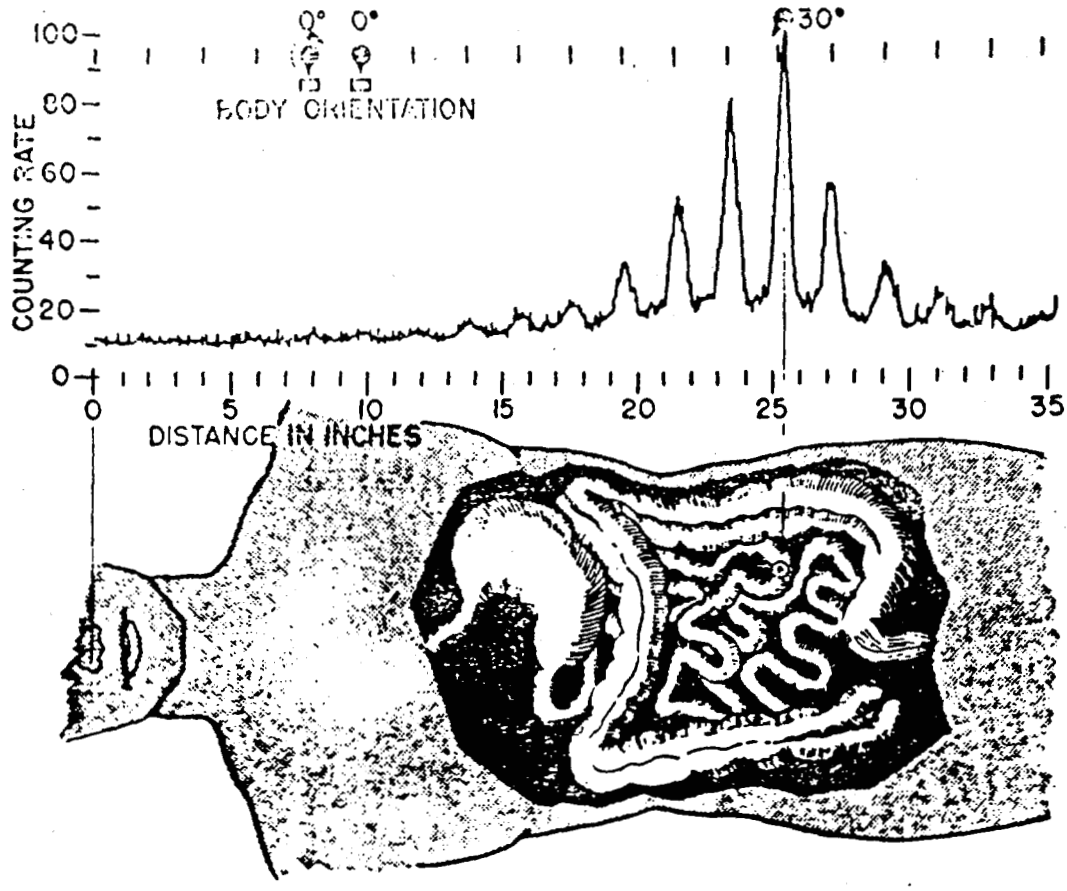

FIG. 12. Helical scan of human body. Point source of manganese-54 in small intestine. 3 in. × 3 in. detector with 3 in. collimator. Scanning rate 2.2 in./min. Body rotating rate 1.2 rpm.

Table 1. Helical scan data for source positions along the GI tract

SCAN NO.	TIME (hrs) AFTER INGESTION	SOURCE DISTANCE FROM NOSE (INCHES)	BODY ORIENTATION (DEGREES)	BODY ORIENTATION DIAGRAM
1	0.2	15	65	
2	1.5	14	90	
3	2.1	15	90	
4	3.5	18	135	
5	4.8	25	45	
6	5.5	25	30	
7	6.9	23	0	
8	7.1	24	180	
9	9.0	19	90	
10	10.8	19	90	
11	13.1	19	90	
12	17.5	21	70	
13	19.3	27	180	

BODY FACING DIRECTLY TOWARD DETECTOR FOR 0° ORIENTATION CLOCKWISE ROTATION

point of the nose (Fig. 13). The orientation of the body for maximum counting rate was approximately 90°, with the left side toward the detector. These results indicate a position of the source in the region of the descending colon, which again is not different from the postulated position for this residence time of the source in the body. Detailed presentation of the data is shown for only three of the thirteen difference scans, but all data are presented in Table 1. Elapsed time after ingestion of the source, distance of the source down the body from the nose, body orientation in degrees with respect to the detector, and the body orientation diagram are tabulated in this table. The results of these thirteen different scans trace the movement of the source along the gastrointestinal tract from 0.2 hr after ingestion

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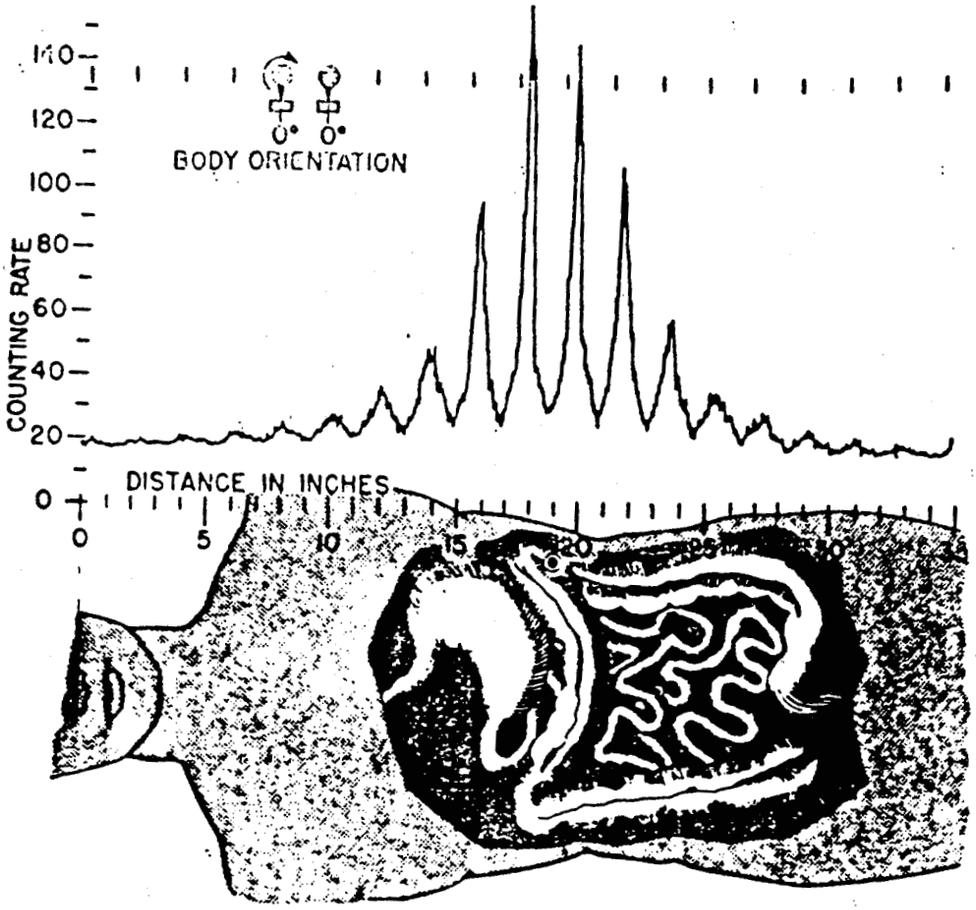

FIG. 13. Helical scan of human body. Point source of manganese-54 in the descending colon. 3 in. × 3 in. detector with 3 in. collimation. Scanning rate 2.2 in/min. Body rotation rate 1.2 rpm.

of the source to the time immediately before elimination in the feces. The body orientation for maximum counting rate and distance along the body remained nearly the same for the first three scans, covering the time period up to 2.1 hr after ingestion. The scans obtained between 3.5 and 7.1 hr indicate source positions in the small intestine and in the upper part of the large intestine. The difference both in body orientation and in source distance down the body from the reference point for the maximum counting rate is clearly indicated. Between 9 hr and 13.1 hr after ingestion of the activity, the peaks remained at 19 in. with a body orientation of 90°. The indicated position of the source, derived from these data, is in the descending colon. At 17.5 hr, the direction of movement was toward the ventral side of the body (70°) and the distance down the body increased to 21 in. The maximum distance recorded was 27 in., and the peaks occurred with the body facing directly away from the detector at 180°. The source was eliminated in the feces shortly after this last scan.

SUMMARY

The rota-scan technique of whole-body counting is an effective method of monitoring human subjects for internal exposures to radionuclides. The method is simple and reliable, rendering information concerning the amount and the position of radionuclides in the body in a single counting operation. Using equal crystal volumes, the sensitivity for the new method is comparable with conventional methods of static counting, and the results

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are much more accurate. Research, involving more sophisticated instrumentation and the use of rotating detectors with the human subject remaining static in the horizontal position, is under way to further develop the technique.

The whole-body counting program for both routine personnel monitoring and research at the National Reactor Testing Station will utilize the rota-scan whole-body counting technique. The method is especially applicable for whole-body counting at the NRTS because of the prevalence of exposures involving insoluble particulate materials containing radionuclides.

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