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COMPUTERIZED HELICAL SCANNING TO DETERMINE THE LOCATION OF SPECIFIC NUCLIDES IN THE HUMAN BODY

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Abstract—The purpose of this investigation was to develop a method to locate and to trace the movement of gamma-emitting nuclides in human subjects by scanning the body helically with a collimated scintillation detector. The counting system was a helical scanner and a 4K analyzer. An IBM 360 computer was used to reduce the counting data. For each scan of the body, as many as 4096 separate measurements were made of the level of activity at positions along the helical path of the detector as it moved around and along the body. The results were in the form of computer-produced isometric and/or isocount contour plots showing the location and relative quantities of the specific nuclides in the different sections of the body. Positions on the surface of the body were plotted as a function of gamma activity and gamma energy. Results are given for 12 scans that were obtained from three different persons. Changes in the distribution of the activity in the body were determined as a function of time by repeated scans of the same individual. The results of this study show that helical scanning can be used to determine the total body distribution of gamma-emitting nuclides in humans. If the helical configuration is used, repeated scans are not necessary in order to cover the surface of the body between the selected limits of the scan. Large quantities of data are rapidly reduced to the final results by a high-speed computer.

INTRODUCTION

HELICAL scanning or rota-scanning has been described as a method of whole-body counting and/or area scanning. Radionuclides were assessed *in vivo* by scanning the body with rotating scintillation detectors[1,2]. Initially, the emphasis was on the utilization of a helical scanner as a whole-body counter. Because of the helical configuration of the scan, the counting geometry of a 4π counter is simulated so that the distribution of activity in the body has less effect on the counting results. Even though a reliable measurement of the total quantity of each radionuclide in the human body is the major concern, the fractional part of each element in each organ or part of the body must be known in order to calculate the organ dose. Fortunately, most organs are not on the central axis of the body and some are very near the surface. Helical scanning is especially applicable for the determination of relative quantities of gamma-emitting elements in these organs because the detector can be made to scan over the entire surface of the trunk of the body, placing it at a minimum distance from each organ at some position along the scan. Up to this time, most area scanning has been by profile scanning or rectilinear scanning. Obviously, multiple scans are required when these techniques are used if the detector is to pass near the critical organs in the body. The purpose of our study was to test helical scanning as a method of area scanning to determine the total-body distribution of gamma-emitting contaminants. A method is described for the application of a large two-parameter analyzer system to accumulate up to 4096 separate counting rates for each scan of the body. Comprehensive computer techniques are described that were employed to reduce these large quantities of data to the final graphical and numerical results.

EXPERIMENTAL

The counting procedure was to scan the human body with rotating detectors.[1] The accumulation and processing of the counting data were accomplished using a helical scanner, a 4096-channel 2-parameter analyzer system, and an IBM 360 computer. Up to 4096 separate numerical values were accumulated by the counting system for each scan of the body. The persons who received these scans were reactor workers who had been exposed accidently and persons who had ingested small

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quantities of radionuclides voluntarily for the purpose of the study. The trunk of the body was scanned helically by 3 × 3 in. NaI(Tl) detectors that were shielded by a 3 or 1 in. diameter cylindrical-bore collimator. The analyzer system included an external time base in order to do timesequence counting, and the experimental configuration of the system could be altered easily by changing the external patch cord connections on the control module. The counting data from each scan of the body were a series of separate gross-gamma counting rates or many separate gamma-ray spectra. These two types of data were accumulated in sequential order as a function of time while the detector moved along its helical path around the body. By synchronizing the timer of the analyzer system with the scanning rate of the detector, specific locations in the memory were made to correspond to definite positions of the detector along its scanning path. Data were read from the magnetic-core memory of the analyzer onto 7-track magnetic tape and finally through a remote input-output terminal (RIOT) into an IBM 360 computer. Data reduction was accomplished by a comprehensive computer program designed to process large numbers of gamma-ray spectra and the many hundreds of sets of numerical values from the different gross-gamma counting rates along the scanning path of the detector. Final results from the computer were obtained in various forms of isocount contour plots of gross-gamma data, isometric plots of multiple gamma-ray spectra, and the numerical values for quantities of different nuclides in different parts of the body.

RESULTS AND DISCUSSION

Determination of the location of gross-gamma activity in the body

Figure 1A shows the results obtained from scanning an individual immediately after voluntarily swallowing a 1.5 μCi source of ^{60}Co. The data for this plot were obtained by scanning the body over the area from the mouth to a position 26 in. further down the longitudinal axis of the body. The plot defines all positions on the surface of the body between these limits. Positions around the body in units of degrees are plotted as a function of distance along the body in inches. The 11 different contour lines

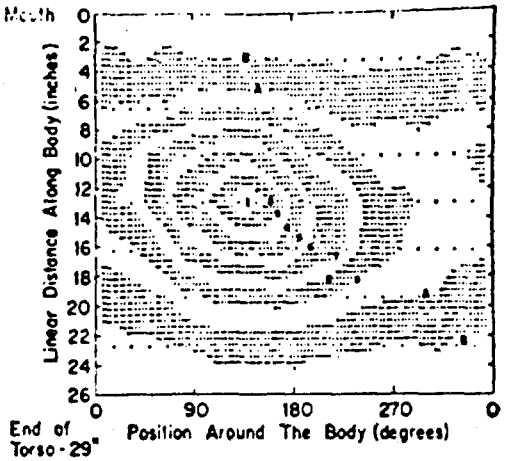

FIG. 1A. First helical scan of the ^{60}Co–^{137}Cs exposure case.

are separated by alternate shaded and blank areas. Each increase of one unit in the number or letter forming the isocount contour lines represents a reduction of 150 units for the isocount value. The range is from a counting rate of 1650 for the position 1 on the plot to a counting rate of 150 at contour line B. A and B are the outer lines, and they are used to define the 10th and 11th contour levels which represent the values 300 and 150, respectively. Rotation of the detector was counterclockwise around the body, so that 0°, 90°, 180° and 270° define positions along a line down the center of the anterior, left, posterior and right sides of the body, respectively. The position on the outside of the body where maximum activity was detected is indicated on the plot at 13 in. below the mouth and at about 135° around the left side of the body from the 0° reference position. This defines a position to the left of the spinal column on the posterior side of the body.

The results shown in Fig. 1B were obtained from a scan of the same person 1.5 hr after the ^{60}Co had been ingested but immediately after an insoluble capsule of ^{137}Cs had been swallowed. Consequently, two sources of activity were present in the body at the time of the scan. The center of the area enclosed by the highest level contour line on the plot is at about 13 in. and 90°. The indicated concentration

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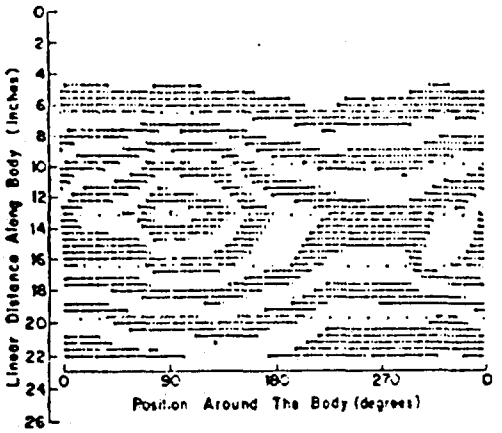

FIG. 1B. Second helical scan of the ^{60}Co–^{137}Cs exposure case.

of activity results from the ^{137}Cs source in the stomach. Another concentration of activity is indicated by the area enclosed by the number 5 and 6 lines. This activity results from the ^{60}Co source that had been ingested 1.5 hr earlier, during which time it has moved toward the right and a few inches farther down the body. Figure 1C is a scan for the same individual at 15.5 hr after the first source was ingested. This scan began at 12 in. below the

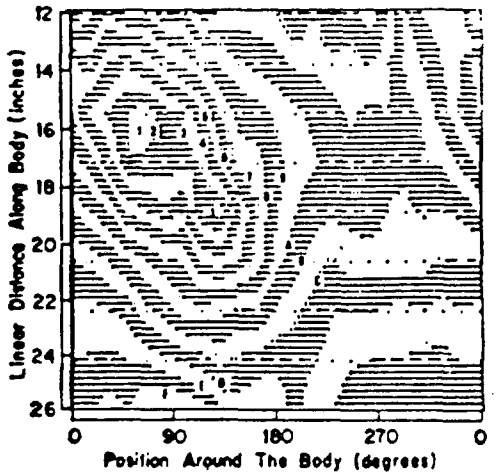

FIG. 1C. Third helical scan of the ^{60}Co–^{137}Cs exposure case.

mouth. Two distinct areas of activity are visible. Both sources are at the same contour level, and both are toward the left side of the body. One source is anterior at about 16 in., and the other is posterior at about 19 in. Their positions were undoubtedly in the lower large intestine at the time of the scan, probably in the descending colon.

The three plots that are labeled Figs. 2A–C are from scans of a reactor worker who had accidently inhaled more than 150 μCi of ^{182}Ta and ^{183}Ta. The direction of rotation of

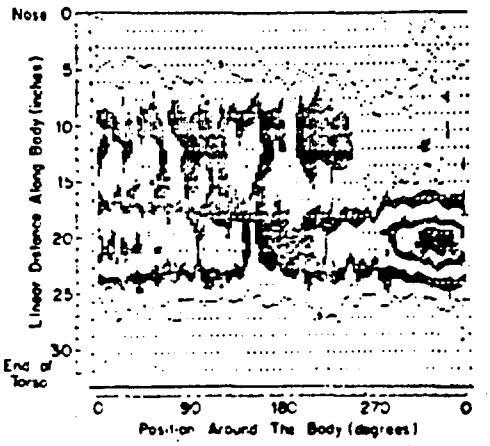

FIG. 2A. First scan of the tantalum exposure case.

the detector for these plots was clockwise beginning with the detector over the nose at center on the anterior side of the body. The nose was used as the zero reference point for the starting position of the detector. Positions indicated by the X axis or degree scale are not the same as those of Fig. 1 because of the reversed direction of rotation. The right and left sides of the body are represented by 90° and 270°, respectively. Figure 2A shows maximum activity in the descending colon at about 21 in. and 330°. This position is on the left side of the body and 21 in. down the longitudinal axis from the nose. In addition to this hot spot and the indication of increased activity most of the way around the body at this level, a concentration of activity is also indicated in the lung area at about 13 in. The number 3

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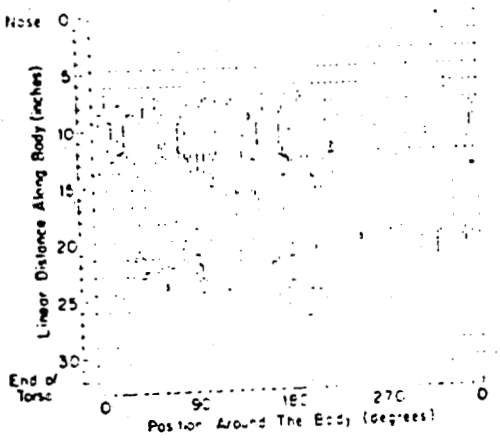

FIG. 2B. Second scan of the tantalum exposure case.

contour line surrounds areas that are centered at about 140° and 225° and 15 in. This defines positions to the right and left of the spinal column in the thoracic region. Increased activity is indicated on both sides of the spinal column. Figure 2B is a scan of the same individual 1 day after the previous scan. Now, three distinct areas of activity are shown by

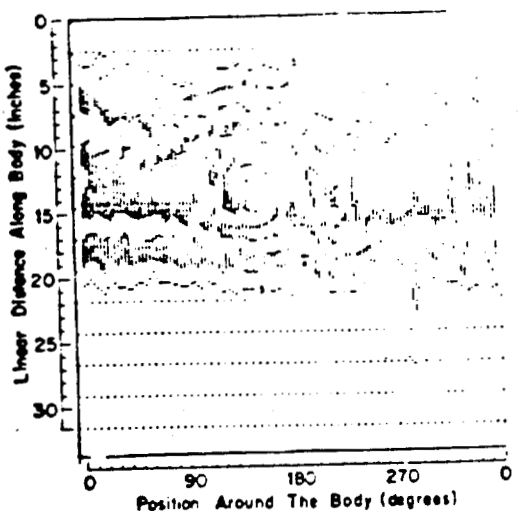

FIG. 2C. Third scan of the tantalum exposure case.

the plot. Activity appears again in the lung area and lower large intestine, but a major peak is at 180° and 25 in. The indicated position of this activity is the extreme lower end of the GI tract, perhaps the rectum. The final contour plot for this series of scans is shown in Fig. 2C. Post-exposure time at the time of this scan was approximately 1 month; the only activity that remained was in the lung. The pattern of the activity distribution has not changed. Again the maximum activity is shown to be at about 13 in., predominating on the right side of the spinal column. The quantity of activity was only about 1 μCi at the time of the scan so that these results were obtained by using the larger 3-in. cylindrical-bore collimator with the 3 × 3 in. detector.

Determinations of the distribution of each separate nuclide in the body

The first trials to locate specific nuclides separately in the body were made by scanning

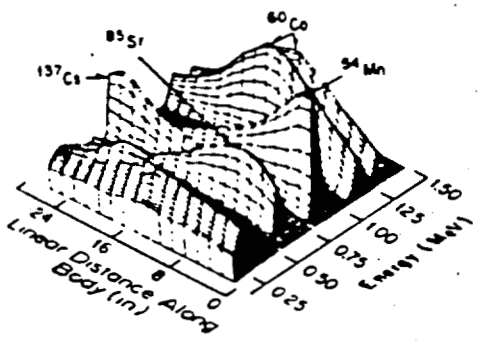

FIG. 3. Helical scan of phantom containing sources of ^{54}Mn, ^{85}Sr, ^{60}Co and ^{137}Cs.

a phantom containing sources of ^{54}Mn, ^{85}Sr, ^{60}Co and ^{137}Cs. A separate spectrum was accumulated for each of 16 different revolutions of the detector around the body while the detector moved 27 in. parallel to the central axis of the body. Therefore, each spectrum resulted from gamma activity in one of 16 cross-sectional areas. The results are shown in Fig. 3 as a computer-produced isometric plot of the 16 spectra. The order of positioning of these four different sources along the body is readily discernible from the plot. The position of maximum activity appears on the

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distance axis at 0 in. for the 0.84-MeV peak of ^{54}Mn, at 8 in. for the 0.51-MeV peak of ^{85}Sr, at 16 in. for the 1.17- and 1.33-MeV peaks of ^{60}Co, and at 24 in. for the 0.66-MeV peak of ^{137}Cs. The computer produced 17 sets of numerical results to show height, position, width and area of each peak in the spectra. The seventeenth spectrum was obtained from the composite spectrum from summation of spectra 1 through 16 as they appear in the isometric plot. Therefore, the peak areas from the composite spectrum represented the total activity of each of the 5 nuclides in the whole body. Quantities of each isotope for each of 16 different cross-sectional areas along the body were given by each of the other 16 similar sets of numerical values from the computer. The computer program is designed to convert peak areas and channel numbers to microcuries and energies when the counting efficiency and the linear correction for sodium iodide are included as input to the computer.

After four different nuclides had been successfully localized in a phantom, the next trial was to trace two different nuclides through the body of a human subject. This individual ingested two different insoluble capsules. One capsule contained 1.5 μCi of ^{60}Co, and the other 1.5 μCi of ^{137}Cs. Scans were made at different times over a 30-hr period while the sources moved through the GI tract. Figures 4A–D are typical of the many different computer-produced plots for these scans with each plot showing different positioning of the ^{60}Co and Cs^{137} along the GI tract. A 3-in. NaI(Tl) crystal with a 3-in. collimator was used as the detector. Eight spectra were accumulated while this collimated detector moved from a position over the mouth to a position 26 in. down the longitudinal axis of the body as it rotated 8 times around the body. Figure 4A shows two different isometric plots from the same data with the view angle differing by 180°. The ^{60}Co with its 1.17- and 1.33-MeV peaks had been ingested about 1.5 hr prior to the scan and the ^{137}Cs source was held in the mouth while the counting data were accumulated. The results show the 0.66-MeV peak for ^{137}Cs at the zero or starting position of the scan which was over the mouth. The centroid of the 1.17- and 1.33-MeV peaks of ^{60}Co are approximately 16 in. down the body from this reference point.

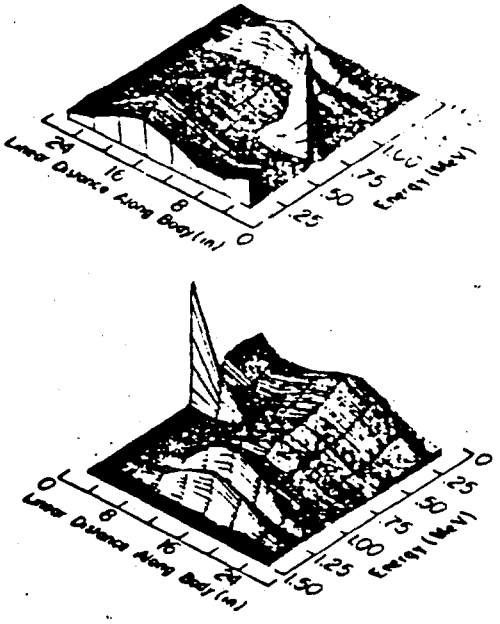

FIG. 4A. First isometric plot from the helical scan of the ^{60}Co–^{137}Cs exposure case.

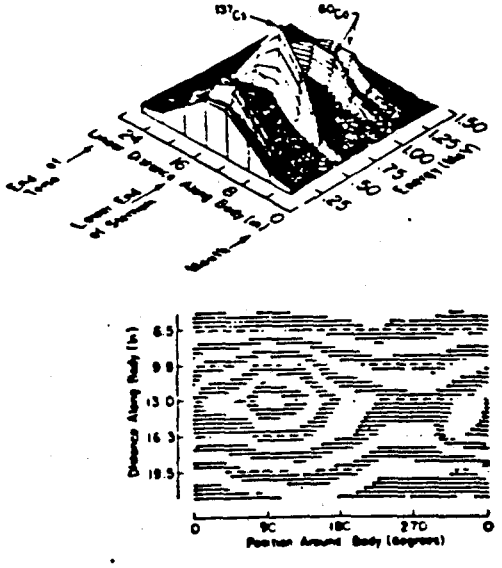

FIG. 4B. Second isometric plot from the helical scan of the ^{60}Co–^{137}Cs exposure case.

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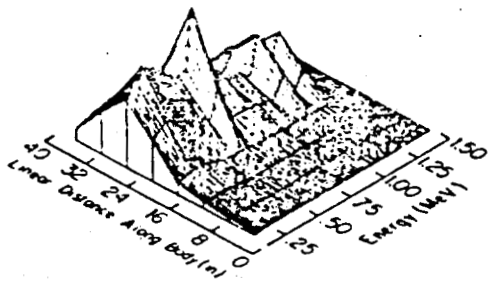

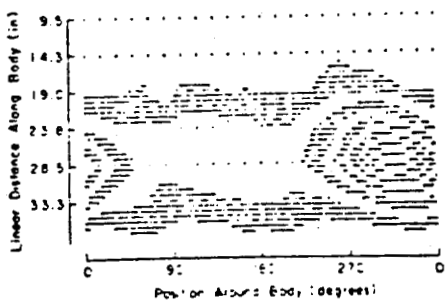

FIG. 4C. Third isometric plot from the helical scan of the ^{60}Co–^{137}Cs exposure case.

Figure 4B shows results from a scan of the same person immediately after the ^{137}Cs source had been swallowed. The isocount contour plot underneath the isometric plot is included to show the distribution of the gross activity. Position around the body is an additional parameter defined by this plot that can be used to localize the activity more exactly. The data for both plots were collected simultaneously by use of identical detectors. The position of the peaks on the distance axis match the highest level on the contour plot at 13 in., and the highest activity is shown by the contour plot to be centered at about 100°. The 100° value represents a location posterior and toward the left side of the body. The centroid for the broad peaks of ^{60}Co on the isometric plot appear to be 2 or 3 in. below the ^{137}Cs peak. The number 5 and 6 contour lines show this activity to be centered at about 330°. However, the two sources are not well resolved on the contour plot. This would obviously require a greater degree of collimation than was provided by the 3-in. collimator. The elapsed time between ingestion of the sources was only 1.5 hr so their locations could have been very nearly the same at the time of the scan.

Figure 4C shows the results of scans of the same individual at about 24 hr after the sources of ^{60}Co and ^{137}Cs had been ingested. Now,

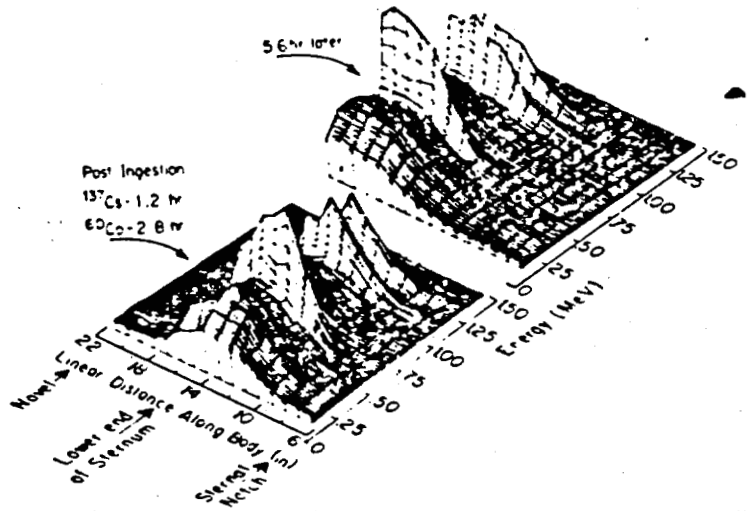

FIG. 4D. Helical scanning results for the ^{60}Co–^{137}Cs exposure case using a 1-in. collimator.

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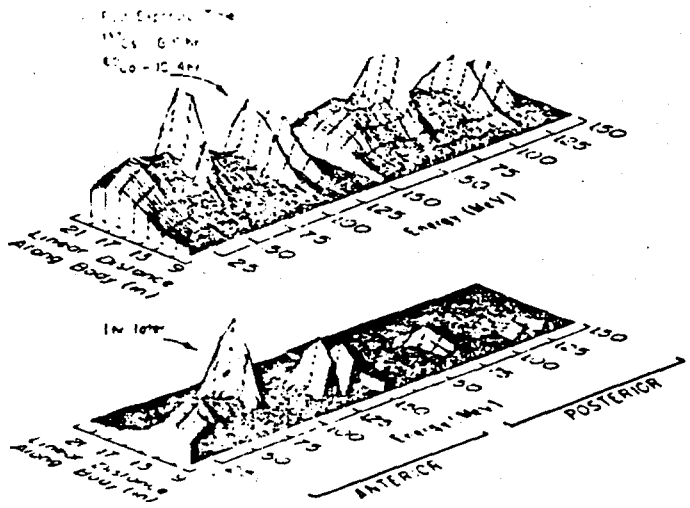

FIG. 5. Double isometric plots for the ^{60}Co–^{137}Cs exposure case.

the two sources appear at the same position on both of the plots. Again, the locations of the two sources were not sufficiently different to be resolved by the 3-in. collimators that were used for this scan. All peaks are at about 2[illegible] in. on the isometric plot and the highest level contour is at this same position. From this contour plot, the position around the body where maximum activity was detected is 3[illegible] and defines a location that is anterior and toward the right side of the body.

Figure 4D was obtained by scanning with a 3 × 3 in. detector with a 1-in. collimator. Sixteen spectra were accumulated for each of these two scans. Peak positions are at 12 in. for the 0.66-MeV peak of ^{137}Cs and 14 in. for the 1.17- and 1.33-MeV peaks for ^{60}Co. After 5.6 hr, the upper edge of all three peaks are off scale, as shown by the upper plot. This plot shows the peaks at about 21 in. The resolution on the distance axis is less for the upper plot indicating increased distance of the source from the detector. The increased build-up on the trailing edges of these spectra indicate movement of the source while the scan was in progress.

Figure 5 shows two double isometric plots. Two spectra were accumulated per single revolution of the detector around the body, one for the anterior and one for the posterior side. The pronounced difference in the peak heights for the two helical scans indicate a pronounced change in position of the sources with respect to the cross-sectional area of the body. The sources have moved much nearer the anterior side of the body during the 1-hr elapsed time between scans. As demonstrated by these plots, one or more pairs of isometric plots can be displayed in this manner for a single scan. Sets of data accumulated on opposite sides of the body can be used in pairs to indicate the depth of a radioactive source in the body. The numerical values for ratios of gamma intensities on opposite sides of the body can be expressed as a function of depth of the radioactive source in the body.

Figure 6 shows results for a scan of a reactor worker who had received an internal exposure from inhalation of airborne activity. Even though the total activity was only approximately 1 μCi and the counting time 6.4 min, location of three different nuclides is discernible from the plot. The peaks in the spectra from ^{106}Ru, ^{95}Zr–^{95}Nb and ^{60}Co are all located at about the level of the sternal notch. All of these nuclides were undoubtedly in the upper respiratory tract at the time of this scan. Most of this activity was eliminated from the body in

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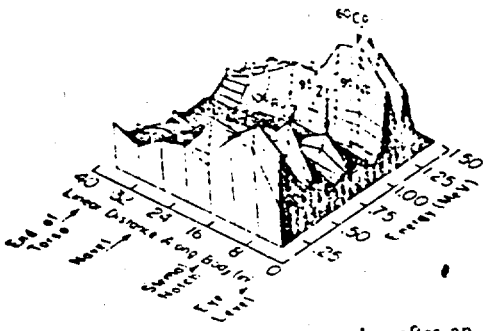

FIG. 6. Helical scan of reactor worker after an accidental inhalation exposure.

the feces within 24 hr after these results were obtained.

A helical scanner with a large-memory analyzer has been used effectively to localize either the gross-gamma activity or specific radionuclides in the human body. The subsequent large quantities of counting data that were accumulated for each scan of the body were reduced to meaningful results by the large IBM 360 computer. A continued investigation is underway to increase the spatial resolution of the counting system by the utilization of large scintillation detectors with focusing collimators. The computer programs are being applied to some of the conventional methods that are used to determine the distribution of radionuclides in human subjects. Also, these programs with the IBM 360 computer have been used with different scanning systems to trace nuclides dynamically inside the body.

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