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The Design and Use of a Linear Scanner[1,2]

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Determination of the amount of radioiodine present in the thyroid gland has been of immeasurable value in the study of the function and diseases of that organ. Similar measurements of the amount of radioactive material in other organs have not been possible because of their relative inaccessibility and variable size. In 1950, Pochin (1) developed a linear or profile scanner with which he demonstrated the distribution of radioactive iodine along the head-toe axis of man, identified sites of radioiodine concentration and estimated the amount of uptake in specific areas.

Since the instrument described by Pochin employed a Geiger-Mueller tube for radiation detection, it was somewhat inefficient for gamma counting. Concannon and Bulhuis (2) developed a linear scanner which was more sensitive since it employed a sodium iodide crystal. Subsequently, Morris (3) described a linear scanner which employed 12 scintillation crystals for detection of radioactivity. The characteristics of the collimation were described in detail and examples of the linear distribution of several isotopes in man were presented (4). The purpose of this paper is to describe a linear scanner which was developed principally for determining the quantitative distribution of iron-59 in man. Experiments are reported which evaluate the sensitivity and resolving capacity of this device and illustrate some of its uses.

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APPARATUS AND METHOD

The linear scanner consists of a table, suitably collimated detectors mounted on a mobile cart and the electronic instruments required to record the data (Fig. 1). The detector assembly consists of two 2 x 2 inch sodium iodide crystals (thallium activated) with attached photomultiplier tubes (Harshaw integral line assemblies type S)[1]. The lead shielding and the mobile cart are illustrated in Figure 2. The cart is propelled beneath the table at a rate of 2.4 inches per minute by a synchronous electric motor (1/150 H.P.). The outputs of the photomultiplier tubes are directed into a preamplifier mixer and then to a single-channel amplifier analyzer (Hamner Model N-302)[2]. The data are collected in a multichannel analyzer (TMC Model 402-A-5)[3] operating in the multiscaler mode. An external timer is used to advance the channel every nine seconds so that 200 channels are utilized as the detector moves from one end of the table to the other. Each channel, therefore, gathers the counts which occur as the detector moves 0.36 inches. The data are recorded through a digital printer (Hewlett-Packard Model Type 130)[4], or an X-Y plotter (Houston Instrument Company Model HR-97)[5]. More recently, the output of the single-channel analyzer has been directed to a digital ratemeter (Baird-Atomic Model 425A)[6] and the data recorded on a strip chart recorder and a digital printer (Baird-Atomic Model 610)[6].

Prior to scanning, the gain on the single-channel analyzer is adjusted so that the photo peak is included in the window of this analyzer. Each time a linear scan is performed, a standard point source (1 ml in a 1 ml tuberculin syringe) of the same radioisotope, is also scanned. The total counts from this source, minus room background, are recorded. This value is used as a corrective measure for physical decay and variation in instrument performance.

Along its long axis, the table is marked in gradations so that the location of a source on the table, can be related to specific channels in the multichannel analyzer. When patients are scanned, they are carefully positioned in the center of the table. The vertex of the skull and the plantar surfaces of the feet are placed within the areas scanned by the detectors and the positions of each related to the gradations on the table top. The other reference points on the body are the acromion, the nipple line, the lower costal margin (in the midaxillary line), the greater trochanter and the middle of the patella. The segments separated by these landmarks are designated as the head and neck, chest, upper abdomen, pelvis, thighs and legs, respectively.

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[1]Harshaw Chemical Company, Cleveland, Ohio.

[2]Hamner Electronics Company, Inc., Princeton, New Jersey.

[3]Technical Measurements Corporation, North Haven, Connecticut.

[4]Hewlett-Packard, Palo Alto, California.

[5]Houston Instrument Company, Houston, Texas.

[6]Baird-Atomic, Inc., Cambridge, Massachusetts.

RESULTS

Evaluation of the Counting System. Analysis of a linear scan of a small source (right circular cylinder 0.5 cm. diameter by 1 cm. length) of ^{59}Fe ferrous citrate (10 μc) reveals a prominent peak over the source, a valley on both sides with a slight increase in counts, starting approximately one foot from the source, reaching a maximum, approximately at 2.5 feet (Fig. 3). The configuration of the collimators indicates that a point source would obtain an unobstructed view of the detectors throughout a distance equivalent to 8.6 channels. The counts recorded in the five channels on each side of the source are therefore designated as target counts and those in the remaining channels as nontarget counts. Nontarget counts result from radiation which passes through the lead shielding prior to striking the detector. Their distribution is due to variation in thickness of the lead, between the source and the detector, as the scanner moves beneath the table and to the distance of the source from the detectors.

In three experiments with point sources, the nontarget counts represented 18.0 $\pm$ 0.5 per cent in the total counts recorded, as the scanner moved 72 inches. If it is assumed that the nontarget radiation is uniformly distributed along the length of the scan, then the actual radiation arising from any point or segment can be calculated, even though several radioactive sources are present. The total

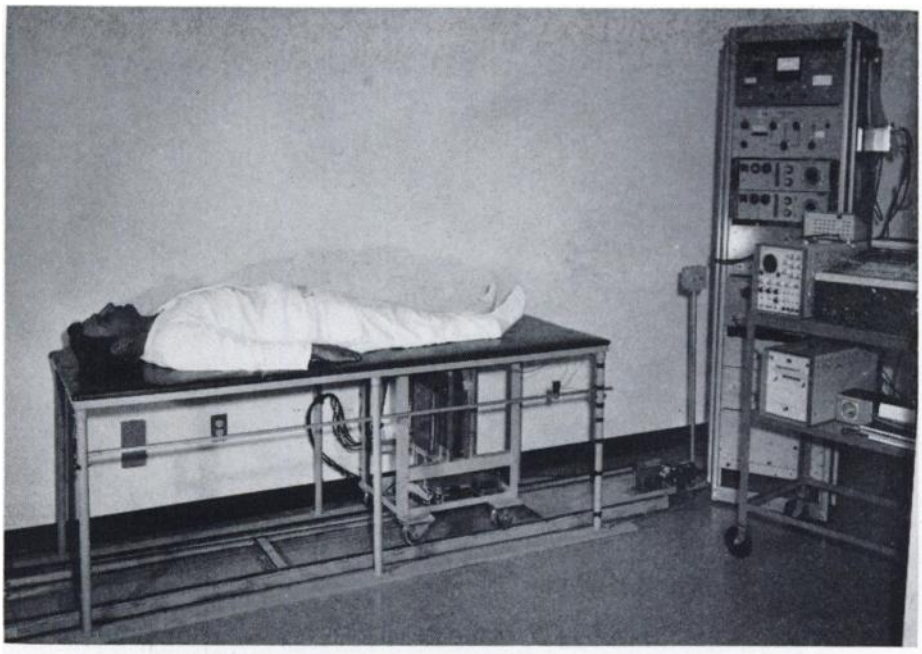

Fig. 1. Photograph of table and instruments employed for linear scanning.

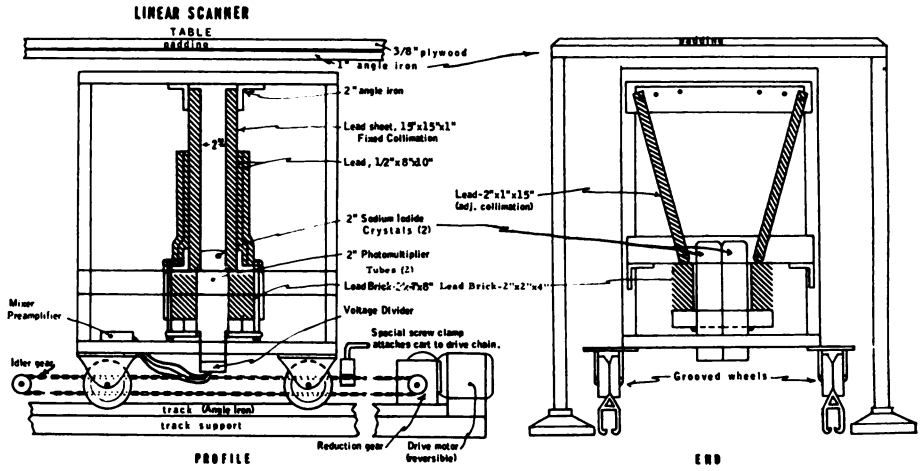

Fig. 2. Diagram of the detectors and shielding used in the linear scanner.

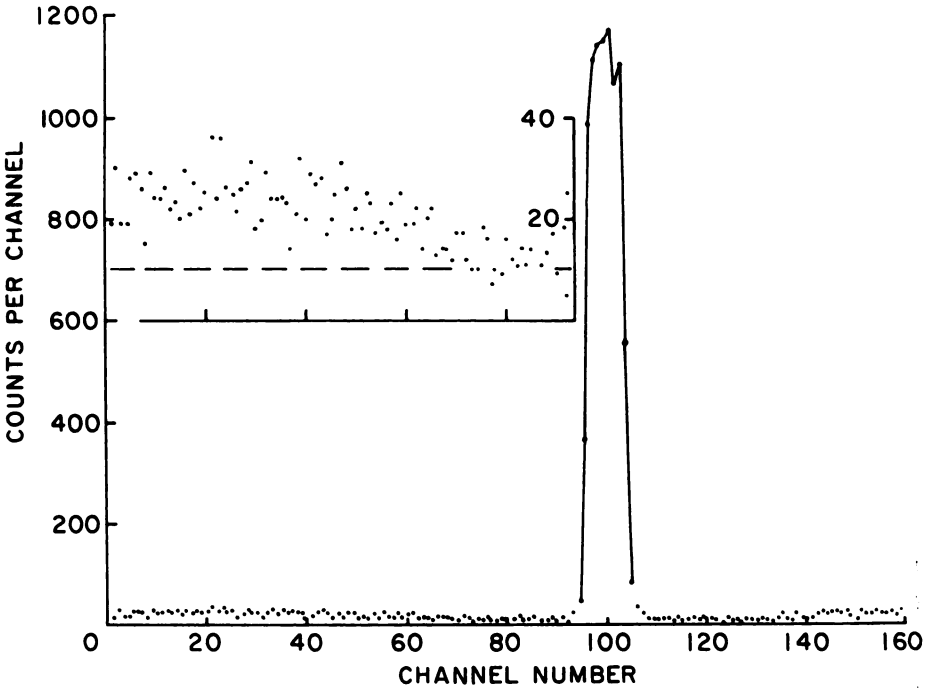

Fig. 3. The linear distribution of counts per channel when a 10 μc "point source" was placed on the midline of the table 36 inches from each end. The cutout shows the counts per channel between channel 0 and channel 92 with the ordinate magnified. Room background is shown by the dashed line. One channel is equivalent to 0.36 inches.

counts recorded in the channel representing a segment a,b can be expressed as follows: $M = .82\ x + \frac{.18\ (C\text{-}x)\ (b\text{-}a)}{200 - (b\text{-}a)}$ where M is the total number of counts recorded when the scanner is directly beneath a segment delimited by channel numbers a and b; C is the total number of counts recorded from all sources as the scanner moved from channel 0 to 200; and x is the total counts recorded from a source (located in segment a, b) in all 200 channels. Using this factor, the mean nontarget radioactivity is eliminated, but an error will be introduced because the radiation penetrating the collimator is not uniform. The radiation arising from sites 6-12 inches from an intense source will be slightly underestimated and that from sites between 24 and 30 inches from the collimator will be slightly overestimated (Fig. 3). The maximum error which can be introduced by this calculation, estimated from an analysis of the distribution of nontarget counts about a single point source, is for each channel approximately 0.07 per cent of the total counts recorded in all 200 channels.

TABLE I

THE SUM OF THE COUNTS RECORDED FROM A SUBJECT SCANNED BOTH PRONE AND SUPINE WITH A POINT SOURCE FIXED AT SPECIFIC SITES.

Location	*Measured*[1] *Radioactivity*	*Thickness inches*	*Calculated*[1] *Radioactivity*
Anterior forehead	1439	7.5	2295
Lateral anterior chest	1515	7.5	2590
Midline anterior chest	1325	7.5	1945
Posterior pelvis	1295	7.0	1824
Anterior thigh	1459	5.5	2075
Mean			2146
Source at table top	2175		2175

[1]Units are total counts per transit (200 channels).

In order to ascertain the effect of the variation in location of radioactive sites on the total counts recorded, the point source was scanned at various positions. A coordinate system was chosen to describe the position of the source: the origin is on the midline of the table top at one end; x is perpendicular to the long axis of the table in the plane of the table; y is the axis parallel to the long axis of the table in the plane of the table; and z is perpendicular to the plane of the table. X, Y and Z are distances measured in inches along the respective axes.

For the purposes of this paper, the efficiency for any point, P represents the total counts recorded in *one* transit (200 channels) with the source at point P, divided by the total counts per transit when the source was at X = 0, Y = 36 and Z = 0 inches.

The relative efficiency of the scanner for positions of the point source of iron-59 from X equals minus to plus 10 inches was determined at Y = 36″ (Fig. 4). The efficiency decreased slightly from 0 to 8 inches and then declined substantially beyond 8 inches, probably due to the lateral lead shields on the collimator. Since most patients are less than 16 inches wide, the distribution of radioactivity along x should not contribute an error greater than 10 per cent.

The relative efficiency of the scanner for sources located at various sites along the longitudinal (y) axis of the table (X = 0, Z = 0) was determined. Variations in efficiency did not exceed the expected counting error.

Absorption must be taken into account when considering the efficiency as a function of the vertical position (Z) of the source, since within the patient, a source at height Z has Z inches of absorbing tissue between it and the table top. To illustrate the changes, resulting from variation in location along z (X = 0, Y = 36), a point source was counted at selected heights, in a large polyethylene cylinder (diameter = 5.5 inches) containing water. The efficiency of the scanner in counts per transit [F(Z)] was found to relate exponentially to Z (Fig. 5). The slope of F (Z) is -0. 171, when the source is iron-59.

To minimize the effects of absorption, the patients were counted prone and supine. If H is the distance from the front to the back surface of the body of the patient measured along z, a concentration of radioactivity at height Z in the prone positions, is at height (H-Z) in the supine position, assuming that the

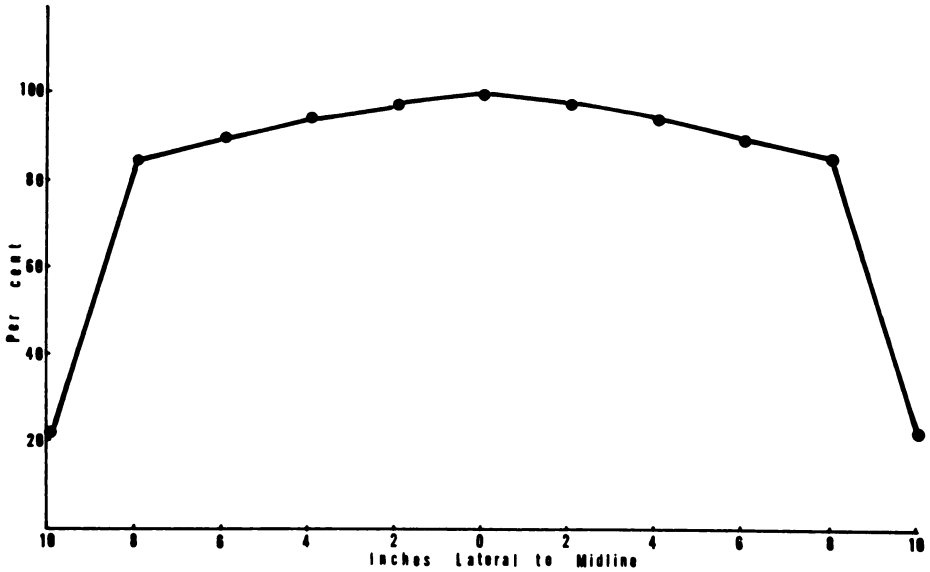

Fig. 4. The relative efficiency of the linear scanner for a point source of radioiron located at various positions along the x axis (Y = 36 inches Z = 0).

internal location of the concentration does not change when the position is altered. Thus, a near-surface source for one scan becomes a deep-lying source for the other. Since the efficiency of the counter [F(Z)] relates exponentially to Z (Fig. 5), the sum of the prone and supine counts is greatest if the source is located at the surface of the body; ie, $A = A_0 (1 + e^{-\mu h})$ where μ = the absorption coefficient and h the height of fluid in the container (or the thickness of the patient); A_0 is the actual radioactivity in counts per transit; and A is the measured radioactivity in counts per transit. The sum of the counts is least if the source is located in the center of the body $A = 2A_0 e^{-\frac{1}{2}\mu h}$. An intermediate value is obtained if the source is uniformly distributed throughout the container $A = \frac{2 A_0 (1 - e^{-\mu h})}{\mu h}$. The variance of these values is illustrated in Figure 6 for an iron-59 source in water. Since all organs have a finite thickness and since the

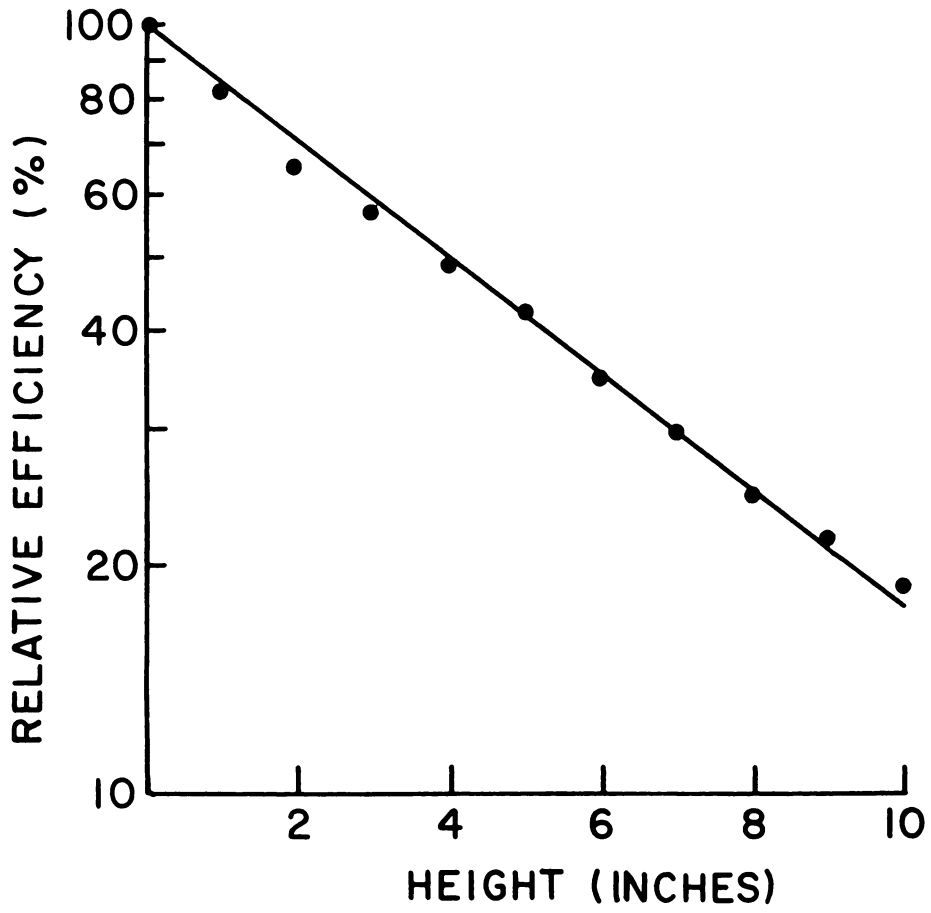

Fig. 5. The relative efficiency of the linear scanner for a point source of radioiron located at various positions along the z axis (X = 0, Y = 36 inches).

value for a diffusely distributed source lies between those for externally situated and internally situated sources, we have calculated the radioactivity expected at table top in segments of the body, according to the following formula: $A_o = \frac{A\,\mu h}{2(1-e^{-\mu h})}$; i.e., as a diffusely distributed source. For the purpose of these studies, we have assumed that the absorbing characteristics of a cross section of man are similar to water.

In order to test the assumptions noted above, a small source was taped at various sites on a normal subject, who was then scanned, repetitively, both prone and supine. The calculated values (Table I) were somewhat low when the source was placed over bone and somewhat high, when the air-filled lung was between the source and the detectors on the prone or supine scan. The mean of the five calculated values was, however, almost identical to the value obtained from counting the source at Z = 0. Eight subjects were given 10 μc of ^{59}Fe citrate, orally. After 30 minutes the patients were scanned. We anticipated that only a small fraction of the administered iron would be absorbed and the remainder would be located in a somewhat central position in the gastrointestinal tract. These patients were scanned in the prone and supine positions and the radioactivity calculated as previously described. The calculated values were 95.3 ± 5.2% of the measured radioactivity from an identical source on the top of the table.

In another series of studies 10 μc of ^{59}Fe citrate was placed in the liver of a whole body plastic phantom (Alderson Research Laboratories)[7] and the phantom scanned. If the liver was considered as a diffuse source, the calculated total body radioactivity was 96.5 per cent of a point source of equal radioactivity. When 10 μc of ^{59}Fe was placed in the spleen of this phantom the calculated total body radioactivity was 90.3 per cent of a point source of equal radioactivity. The decreased sensitivity for radiation arising from the spleen can be related to the smaller size and more central location of the spleen.

In order to evaluate the resolving capacity of the linear scanner, iron-59 citrate was poured to a depth of one-half inch in a series of flat rectangular aluminum pans. Each pan was then scanned, with the detector traversing the entire table. The sum of counts detected (above the instrument background) which occurred while the midpoint of the detector was beneath the pan, was then determined. This value was corrected for radiation penetrating the collimator as previously described. The corrected value compared to the total counts recorded after background subtraction. For sources longer than eight inches, more than 90 per cent of the counts were recorded from the segment occupied by the source. For quantitative studies of radioisotope distribution in man, we have limited our consideration to segments longer than eight inches. In studies noted above, of the plastic phantom, more than 95 per cent of the total radiation recorded from the entire body (after correction as previously described), could be localized to the linear segment in which the liver or spleen was contained.

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[7]Alderson Research Laboratories, Stanford, Connecticut.

Application of linear scanning. Subjects were scanned 24 hours following the intravenous injection of transferrin-bound ^{59}Fe, since at this time most of the radioiron is present, either in bone marrow, or in iron stores, principally in the liver (5). In a normal subject, radioiron was in the chest, upper abdomen and in the pelvis, but not in the legs (Figure 7). This distribution of radioiron corresponds to the sites of bone marrow found by postmortem examination of normal adults, who died suddenly, in whom most of the marrow was in the ribs, sternum, vertebrae, pelvic bones and upper femora, but little in the skull and none in the lower femora, tibiae or tarsal bones (6).

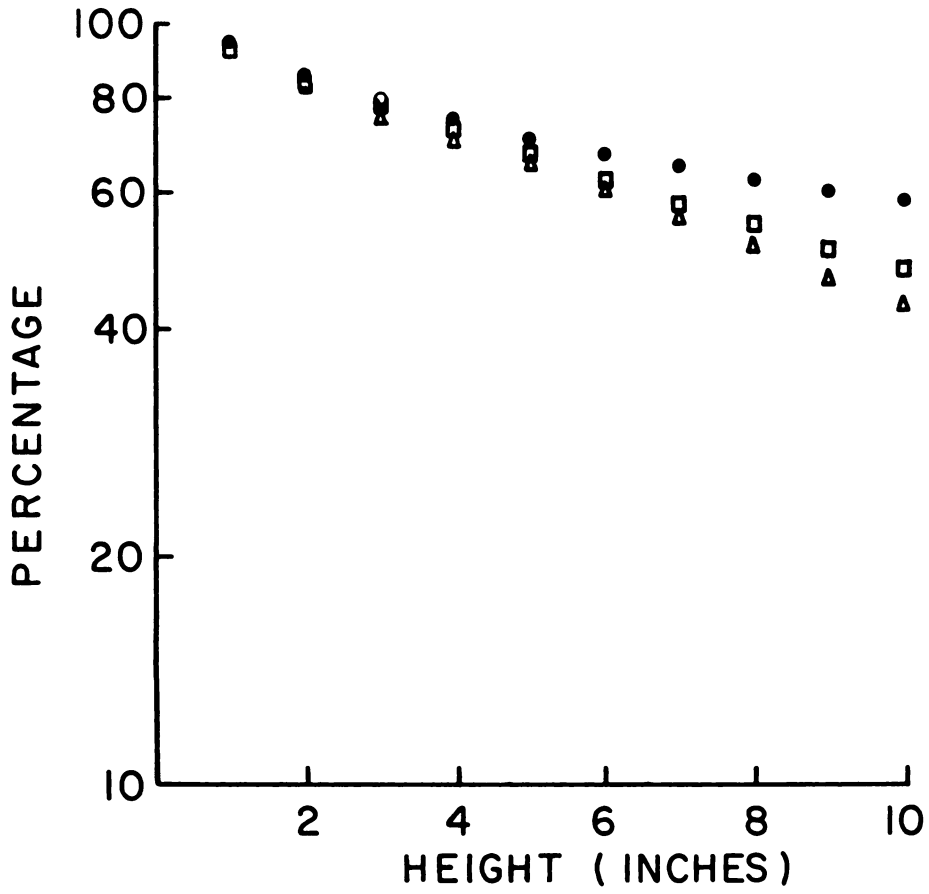

Fig. 6. Predicted values for the sum of the counts recorded by scanning patients prone and supine. Illustrated are the predicted values (expressed as a percentage of counts from a source scanned at H = 0) for a point source located at the anterior or posterior surface (•—•—•); located midway between the anterior and posterior surfaces; (△—△—△); and for a uniformly distributed source (□—□—□). The abscissa is the height (H) of the segment in or on which the source is located.

Scanning of a patient with hemolytic anemia revealed radioiron in the chest, upper abdomen and pelvis, as in the normal subject. In addition, there was a significant amount of radioactivity about the knees and the feet, indicative of red marrow in the lower femora, upper tibiae, lower tibiae and tarsal bones.

The linear scan of a patient with hypoplastic anemia demonstrated some radioactivity over the chest and pelvis, but most of the radioactivity was over the upper abdomen. This is due to the large fraction of the radioiron taken up by the liver. The percentage of total body radioactivity in the upper abdomen (24 hours after injection) in three patients with hypoplastic anemias 56, 54, and 64%, respectively, was significantly greater than in three normal subjects (29, 31 and 27%).

The use of the linear scanner as a whole body counter. The linear scanner can be used as a total body counter for microcurie doses of radioactive materials. Serial scans were performed in three normal subjects at intervals of one to 15 days after the intravenous injection of 10 μc ^{59}Fe. The radioiron was in the bone marrow for the first three to five days after injection and was then incorporated into circulating cells. In each of the three subjects, the relative deviations of the total counts recorded on multiple scans (after correction for physical decay) were 1 per cent, 0.5 per cent and 0.2 per cent, respectively. Thus, the total counts recorded from a patient were relatively independent of the location of the radioisotope in the patient. In studies of a patient with polycythemia vera being phlebotomized, the loss of radioiron predicted from serial body scans never differed more than two per cent from that determined by counting the blood removed.

DISCUSSION

These studies indicate that the linear scanner is of value in: (1) the localization of radioactive sites in man; (2) the determination of the percentage of radioactive material in a particular segment of the body and (3) measurement of the total body radioactivity following administration of microcurie doses of radioisotopes.

Pochin (1) and Pircher and co-workers (4) demonstrated that metastases from carcinoma of the thyroid could be rapidly located using a linear scanner. The linear scanner is particularly suitable since the body can be scanned completely in a relatively short time without repositioning the patient. More recently, Edwards, Andrews, Sitterson and Knisely (7) have used the linear scanner to determine the distribution of bone marrow in man. Since the bones in the lower extremities are linearly distinct from the bones of the trunk, expansion of the marrow into the lower extremity can be measured.

Quantitative determinations of the distribution of radioactivity in the body have several applications. Cunningham, *et al* (8) and Pircher, *et al* (4) used the linear scanner to determine the fraction of ^{131}I localized to metastases of cancer of the thyroid and to measure the rate of disappearance. Such studies should be of considerable value in the estimation of the radiation dose to a particular lesion. From a quantitative analysis of the linear distribution of radioiron

in man, in this laboratory, a method has been developed with which it is possible to estimate the fraction of radioiron present in bone marrow and in the liver, 24 hours after injection (9). These studies will permit the estimation of hepatic and marrow turnover of plasma iron, leading to a better definition of iron metabolism in various anemias.

The present studies illustrate the value of the linear scanner as a total body counter. This might be expected empirically, because as the detector moves

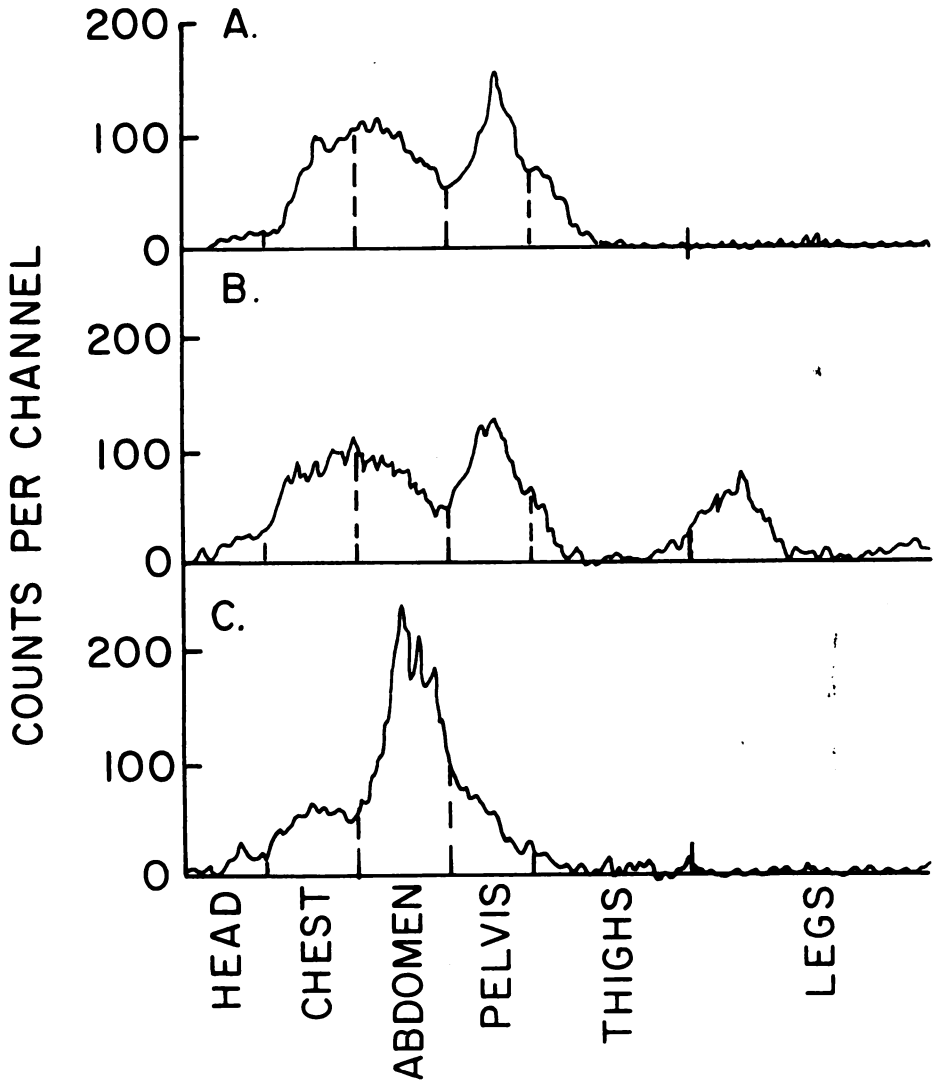

Fig. 7. The linear distribution of radioiron along the head-toe axis 24 hours after injection of transferrin-bound Fe^{59} in a normal subject (A) and in patients with congenital spherocytosis (B) and idiopathic hypoplastic anemia (C).

from the head of the subject to his feet, it "views" every point along the head-toe axis for a similar period of time. One of the major errors encountered in the measurement of total body radioactivity, by various means, relates to radioactive absorption within the body. When the linear scanner is used, a reasonable estimate of this factor can be made.

SUMMARY

The design and calibration of a device for measurement of the distribution of radioactivity along the head-toe axis of man has been described. This device has been used to: (1) to determine the linear distribution of radioiron in man; (2) to determine the percentage of radioactivity in any cross segment of the body and (3) to measure the total body radioactivity following the injection of radioiron. Examples of each of these applications have been presented.

REFERENCES

1. POCHIN, E. E.: Investigation of thyroid function and disease with radioactive iodine. *Lancet.* 2:84, 1950.

2. CONCANNON, J. P., AND BULHUIS, R. T.: Studies with a modified collimator for use with a scintillation counter for total body scanning. *Am. J. Roentgenol.* 78:855, 1957.

3. MORRIS, A. C., JR.: A linear scanner for human radioisotope research. U.S. Atomic Energy Commission, Technical Information Service, Oak Ridge Institute of Nuclear Studies, Inc., Oak Ridge, Tenn., ORINS-33, August, 1960.

4. PIRCHER, F., ANDREWS, G. A., BRUCER, M., AND ROSS, D. A.: The linear scanner in clinical studies. U.S. Atomic Energy Commission, Technical Information Service, Oak Ridge Institute of Nuclear Studies, Inc., Oak Ridge, Tenn., ORINS-36, August, 1960.

5. POLLYCOVE, M. AND MORRIS, R.: The quantitative determination of iron kinetics and hemoglobin synthesis in human subjects. *J. Clin. Invest.* 40:753, 1961.

6. HASHIMOTO, M.: Pathology of bone marrow. *Acta. Haemat.* 27:193, 1962.

7. EDWARDS, C. L., ANDREWS, G. A., SITTERSON, B. W., AND KNISELY, R. M.: Clinical bone marrow scanning with radioisotopes, *Blood* 23:741, 1964.

8. CUNNINGHAM, R. M., HILTON, G., AND POCHIN, E. E.: Radioiodine uptake in thyroid carcinomata. *Brit. J. Radiol.* 28:252, 1955.

9. ALFREY, C. P. AND LYNCH, E. C.: Clearance and turnover of plasma iron by sites of erythropoiesis and iron storage. To be submitted for publication to *Am. J. Med.*

Nuclear Medical Session At AMA Convention June 16-20, 1968

A session on Nuclear Medicine will be presented under the miscellaneous topics portion of the program at the American Medical Association annual convention to be held in San Francisco, June 16-20, 1968. This convention will be held one week in advance of the Society of Nuclear Medicine annual meeting in St. Louis.

Anyone wishing to present a paper at the AMA meeting should send an abstract to Dr. Malcolm Powell, no later than February 1, 1968. Papers on subjects of general interest to the medical profession will be given preference over highly technical or research oriented presentations. This meeting is an excellent opportunity for familiarization of the medical community with available techniques in Nuclear Medicine.

Persons wishing to show a scientific exhibit in the field of Nuclear Medicine should send a description of the exhibit to the chairman of the Scientific Exhibit program, as directed by the announcements in the Journal of the American Medical Association.

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