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The Hybrid Radioisotope Scanner[1]

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In this laboratory, a radioisotope mapping instrument has been developed which is intermediate in speed and complexity between a mechanical rectilinear scanner and a stationary camera-type device such as the Gamma-Ray Camera of H. Anger (1) or the Autofluoroscope of Bender and Blau (2). In this new device, the distribution of activity in the transverse direction across the subject is translated into a corresponding distribution of detected events in a long rod-shaped detector. This latter distribution is then sensed electronically. The complete area map is generated by mechanically moving the subject longitudinally, in a direction perpendicular to the long axis of the detector. Because of this combination of an electronically sensed transverse scan with a mechanical longitudinal scan, the instrument has been called the hybrid scanner.

DESIGN OF THE HYBRID SCANNER

The scanning process of the hybrid instrument depends upon the following observation: When a scintillation event occurs in a long rod of fluor, the logarithm of the ratio of the fluorescent radiation fluxes issuing from opposite ends of the rod, to a close approximation, is directly proportional to the position of the scintillation event in the direction parallel to the long axis of the rod (3). This principle forms the basis of a particularly simple method of determining the position of a scintillation event.

The main components of the present version of this instrument are indicated

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schematically in Fig. 1, and a general view of the scanner is shown in Figure 2. The detector is a two inch diameter by eight inch long NaI(Tl) scintillation crystal, with two inch diameter multiplier phototubes bonded to either end. The crystal and phototubes are sealed within a light-tight, low-mass housing (4), and the entire assembly is placed within a massive lead shield (Fig. 3). The upper face of the shield contains a linear collimator, which will be described later; the subject is placed above this collimator on a light-weight wheeled cot, two feet wide by six feet long.

For each scintillation event in the crystal, the end-viewing multiplier phototube pulses are relayed via preamplifiers to two conventional linear amplifiers. The amplifier output pulses are stretched and then processed by a logarithmic converter which provides an output signal proportional to ($\log V_1 - \log V_2$), or $\log (V_1/V_2)$, where V_1 and V_2 are the amplitudes of the multiplier phototube pulses. This converter output is applied directly to the vertical input of a read-out cathode ray oscilloscope.

The linear amplifier output pulses are also summed and presented to a wide-window pulse height analyzer. With the present detector, this summed pulse is very nearly independent of the position of the scintillation, the end-to-

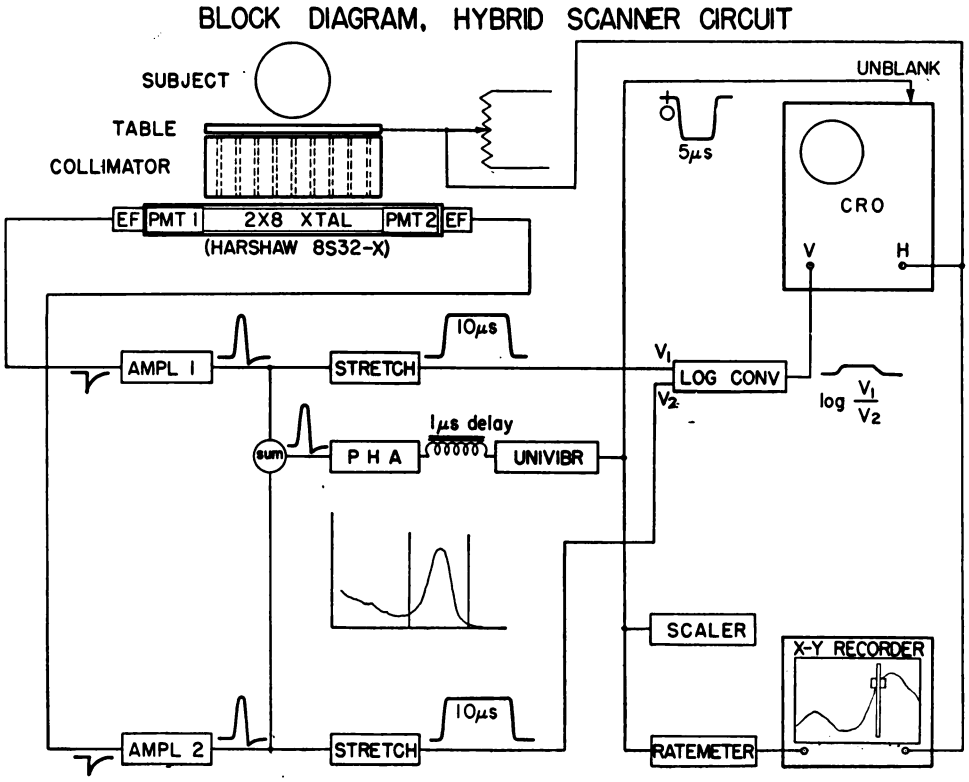

Fig. 1. Schematic diagram of the hybrid scanner system. As drawn, the motion of the cot on which the subject rests is perpendicular to the plane of the figure. Not shown is the camera which photographs the pattern of spots presented on the read-out oscilloscope screen.

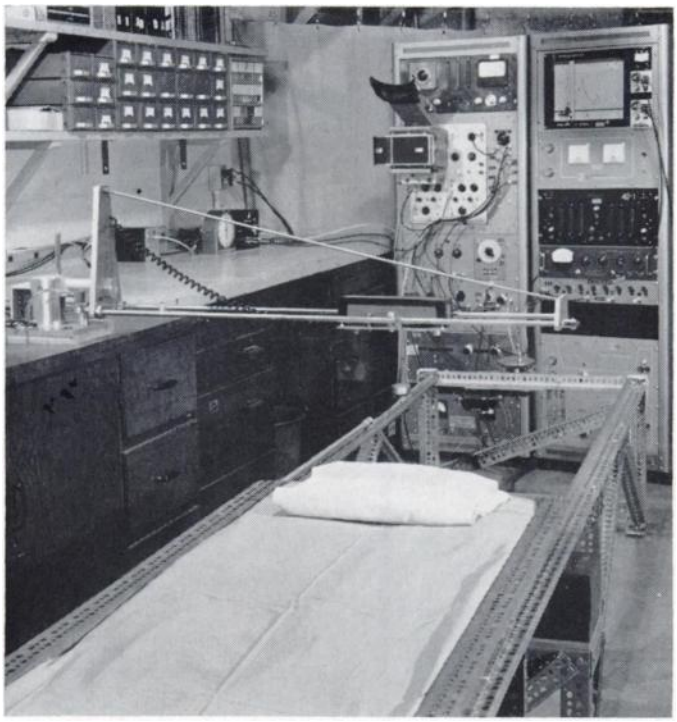

Fig. 2. General view of the hybrid scanner. The wheeled cot on its track is seen in the foreground, and the electronic components and read-out oscilloscope are to the rear. The marker lamp box on its track is suspended over the cot, directly above the detector head.

center variation in pulse height being only about five percent, and pulse height analysis of this position-independent, energy-dependent summed pulse allows the rejection of scattered photons. The pulse height analyzer, in turn, drives a univibrator which supplies a carefully stabilized beam unblanking pulse to the read-out cathode ray oscilloscope.

Thus, a bright spot is formed on the oscilloscope screen for each scintillation event which passes the pulse height analyzer; the displacement of this spot along the vertical is proportional to the logarithm of the ratio of the pulses delivered by the two multiplier phototubes end-viewing the crystal, and hence to the position of the scintillation event. This constitutes the electronic transverse scanning process and develops one direction of the map.

To generate the complete area map, the cot holding the subject is moved by a small variable speed motor along a horizontal track over the stationary detector. A total travel of slightly over six feet is available, at speeds up to five inches per minute. As the subject is moved across the detector, a multiturn potentiometer coupled to the cot delivers a voltage directly proportional to cot position to the horizontal input of the read-out oscilloscope. Hence, as the light spots on the oscilloscope screen are electronically positioned vertically they are simultaneously shifted horizontally in exact synchronism with the longitudinal motion of the subject. A camera focused on the screen integrates all light flashes during the scan, and delivers a finished photographic area map.

The width of the field is limited by the length of the present scintillation crystal to slightly less than eight inches. Typically, the oscilloscope presentation is adjusted so that one centimeter of vertical or horizontal screen deflection corresponds to exactly two inches of transverse or longitudinal displacement on the subject. Because of the film size, this adjustment limits the total length for one scan to about 19 inches; generally, this has proved to be more than adequate. Occasionally, a reduction to one centimeter of screen deflection per four inches on the subject has been employed to allow a continuous 38 inch scan. This length permits full ankle-to-hip leg scans as well as complete head and spinal views.

Profile scanning. As indicated in Fig. 1, the unblanking univibrator also drives a scaler and ratemeter. The former instrument, with its associated timer, is used to integrate all counts recorded during a scan, and to measure the elapsed time of the procedure. The ratemeter is used in adjustment of the instrument prior to mapping, but serves primarily to provide a signal for one axis of an X-Y recorder, the other axis of which is driven by the cot position potentiometer. Since the ratemeter is responding to the total activity across the field width, the recorder generates a profile scan of the subject (5).

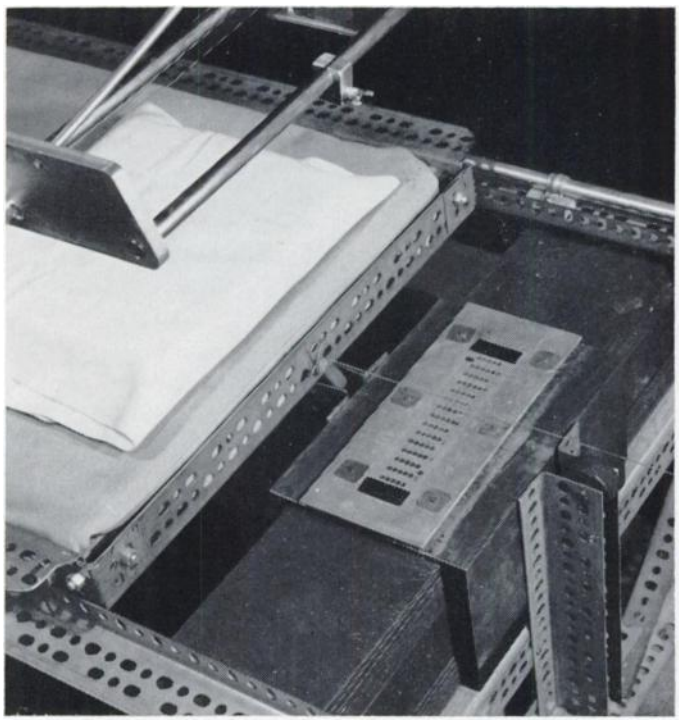

Fig. 3. The detector head of the hybrid scanner. The aluminum top plate of the mercury-bodied, linear, semi-focusing collimator is raised slightly above the upper surface of the brass-encased central lead shield. The heavy rollers on either side of the shield prevent the cot from sagging against the top plate of the collimator.

This profile scan has proved to be a useful adjunct to the radioisotope map. Potentially, profile scanning may be used to rapidly locate areas of interest, which may then be mapped in detail. It is convenient to be able to perform both types of measurement on the same instrument, and, if desired, simultaneously.

Subject placement and map orientation. In Figures 2, 3, a track suspended over the patient cot is seen. This track is aligned parallel to the long axis of the crystal, and is permanently fixed with respect to the detector. A small box carried on the track contains two lamps positioned such that when the box is moved to a marked central position, the lamp beams project vertically downward in line with the extreme ends of the collimator. These light beams thus mark the scan limits, and the subject can be shifted laterally on the cot (or the entire cot and track can be shifted independently of the detector) to place the desired area of the subject in the mapping field.

One of the lamps also provides a marker light for orientation of the map with anatomical landmarks and contours of the subject. These features are traced out by simultaneous motions of the lamp box and the cot, with these movements relayed to the read-out oscilloscope. When a switch on the lamp box is depressed, an unblanking circuit places a brief flash of light on the oscilloscope screen in precisely the same position as would have been occupied by read-out spots generated by radiation emanating from the position of the subject indicated by the marker light.

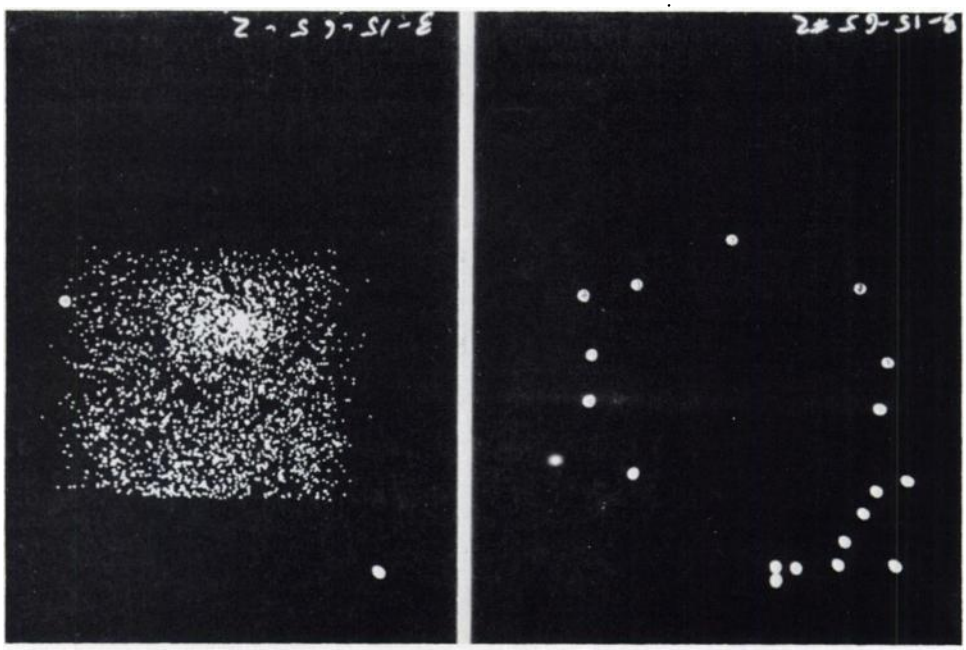

Fig. 4. A pair of primary data films. On the left is a dot scan film of a right lateral view of the subject's head, while on the right is a marker film showing the outline of the head. The two alignment marks common to both films allow their superimposition during processing to orient the radioisotope map to the contours of the head. A photographically enhanced reproduction of these films is shown in Fig. 8; the data of interest accompany the latter figure.

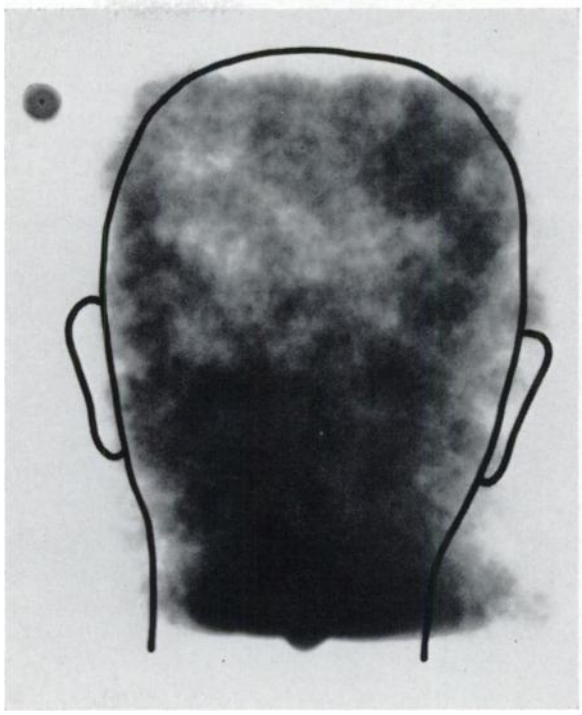

Fig. 5. A PA brain scan made on a patient four days after administration of 800 μC of ^{131}I-labeled antifibrinogen antibody. A metastatic tumor on the right side is clearly seen. Mapping time: 9 minutes, 15 seconds; total counts recorded: 18,177.

In order to avoid placing marker spots over interesting areas of the scan, a second film is always made for map orientation purposes. A typical pair of films is shown in Figure 4. To the left is a brain scan (the details of which will be given later) containing, in addition to the map, two alignment marks well out of the field. On the right is the marker film, containing the same two alignment marks, as well as marks outlining the patient's head. The films may be superimposed by means of the alignment marks. This is demonstrated in Fig. 8, which shows the same scan as Fig. 4 after photographic processing.

Read out. Several different read-out procedures have been used, none of which have proved to be entirely satisfactory in all situations. The current standard method involves in-focus photography of focused oscilloscope spots. Various photographic media are used, with the most common being a rapid developing, continuous tone, positive transparency material (6). The resultant film is similar to a convential dot scan, and frequently may be interpreted immediately. When some degree of area integration, background subtraction, and contrast enhancement are required, the film may be processed by a flying spot scanner (7) and television system (8).

Another method of enhancement of the dot scan film is the out-of-focus enlargement of the film on ordinary projection paper. By trial and error adjustment of enlarger lens aperture, exposure time, and contrast of paper, a reasonable

facsimile of a photoscan is achieved. This is the method used to produce the radioisotope maps presented in this paper.

COLLIMATOR DESIGN

The scintillation position sensing system employed in the hybrid instrument is insensitive to variations in the radial position of a scintillation event in the crystal, but responds only to variations along the axial direction. This implies that the full width of the crystal may be used. For the high efficiency necessary in an instrument intended for rapid mapping, the full width of the crystal must be used. Some form of a focusing collimator, therefore, is required.

This focusing, however, can be employed only in the direction perpendicular to the crystal axis; in the direction along this axis, the collimator channels must remain parallel. Such a design, which is peculiar to the hybrid scanner system, has been termed a linear, semi-focusing collimator.

The collimator presently in use (9) employs a 2.5 inch thick mercury body, with air-filled collimator channels formed by submerging sealed, thin-walled, rigid plastic tubes into the mercury. Each channel is square in cross section, and tapers from 0.27 inches on the side at the crystal face to 0.18 inches on the side at the working face. The collimator is designed around the concept of a *unit array*, which in this model consists of five channels arranged across the crystal

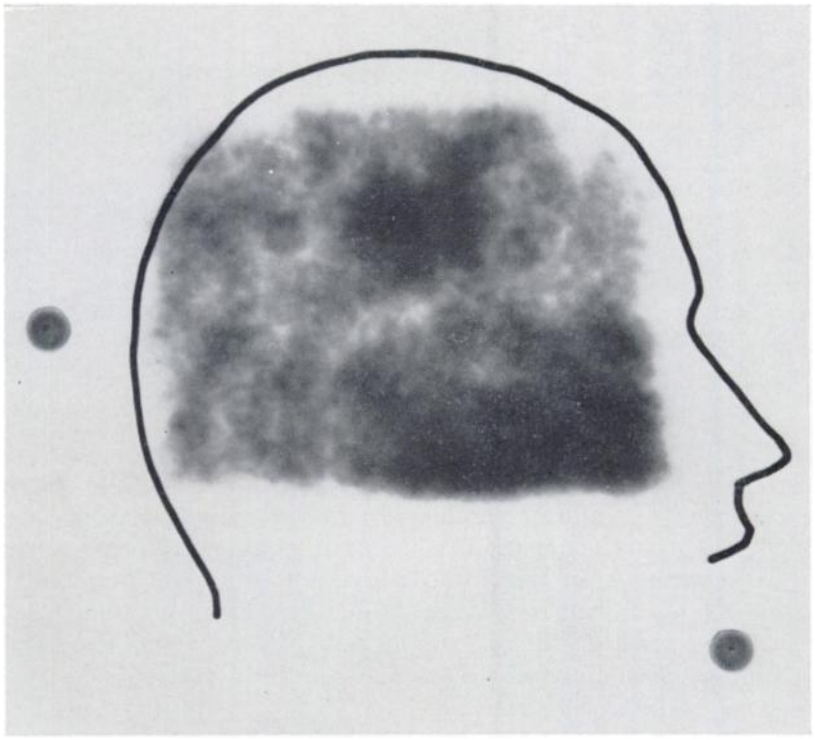

Fig. 6. A right lateral brain scan made immediately following the scan shown in Fig. 5, on the same patient. The tumor is well delineated. Mapping time: 6 minutes; total counts recorded: 11,689.

diameter such that their center lines converge at a common point, 4.5 inches above the working face of the collimator. The center lines of the channels in each unit array are co-planar, with the plane perpendicular to the long axis of the crystal. Each unit array is considered to cover a one-half inch thick slice of the crystal, and the present model consists of 15 identical unit arrays on a one-half inch repeat distance. Thus, 7.5 inches of the total eight inch crystal length are used.

The design of a linear semi-focusing collimator for the present instrument is made more difficult, and its performance is degraded, by the fact that the collimator must view the curved surface of the cylindrical crystal detector. These difficulties would be eliminated, or at least reduced, if the crystal had a square, rather than a circular, cross-section. A crystal with this configuration has been ordered.

PERFORMANCE OF THE HYBRID SCANNER

The linearity of the scintillation position sensing system employed in this instrument is quite good over the central seven inches of the eight inch long crystal, and is independent of photon energy. It is also relatively unaffected by variations in the high voltage supply and amplifier gain shifts.

The spatial resolution of the hybrid scanner is inferior to that of a high-quality rectilinear scanner, but appears to be entirely adequate for most purposes.

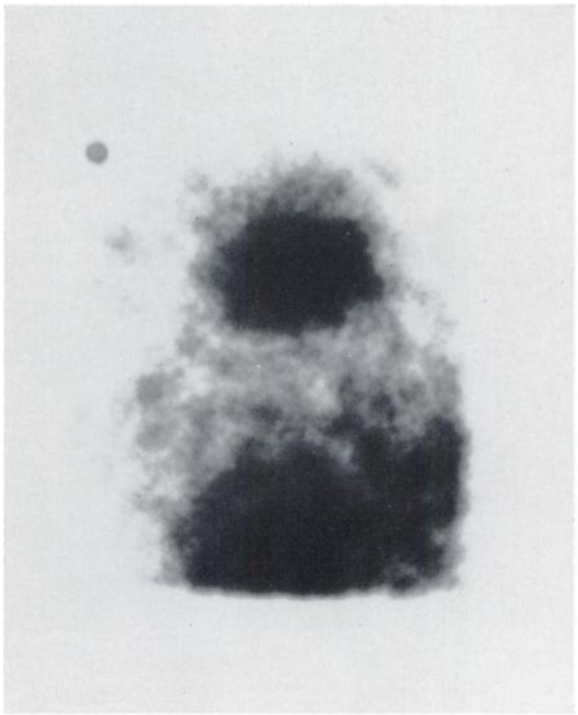

Fig. 7. A right lateral brain scan of the same patient as that of Fig. 5, made 12 days following a therapy injection of 110 mC of ^{131}I-labeled antifibrinogen antibody. Activity was quite high, and the tumor was easily delineated. Mapping time: one minute, 30 seconds; total counts recorded: 34,117.

In the mechanical longitudinal scan direction, resolution is determined by the collimator, and is subject to the same considerations which apply to standard scanning instruments. In the transverse direction, the resolution is influenced both by the collimator and by the inherent resolution of the position sensing system.

This latter has been studied extensively, and will be discussed in detail in a forthcoming report. The general conclusion for the present crystal is that a reasonable Gaussian distribution of read-out spots is produced by a collimated beam of radiation directed perpendicularly to the crystal axis. The full width at half maximum of this distribution (the *resolution distance*) is about 9.5% of the crystal length, or 1.9 cm, for 364 KeV photons. This resolution distance, which compares quite favorably with that of stationary camera devices (10), has been established by direct measurement using a thin sheet of ^{131}I photons intercepting the full crystal diameter, and employing efficient wide-window pulse height analysis.

Mathematical model studies have indicated that the resolution distance should be proportional to the length of the crystal, and inversely proportional to the square root of the photon energy. An important conclusion of these model studies is that this resolution distance can be significantly improved by proper design of the scintillation crystal package. The conditions for optimum detector

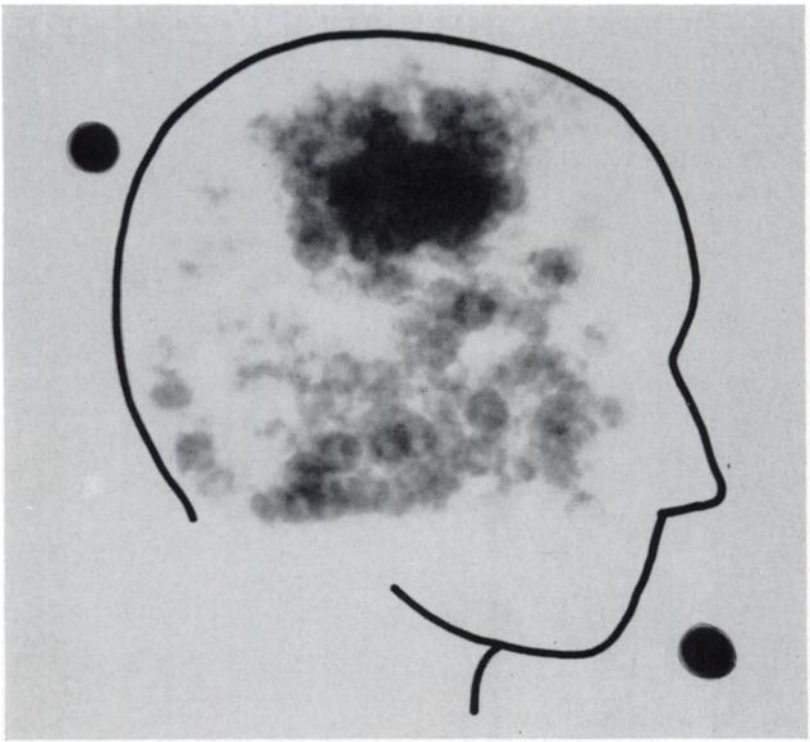

Fig. 8. A right lateral brain scan of the same patient as that of Fig. 5, made 33 days after the therapy injection described in Fig. 7. Tumor activity was now quite low, but the target-to-non-target ratio was very high, allowing good delineation of the tumor. The primary data films from which this photographically enhanced print was made are shown in Fig. 4. Mapping time: 3 minutes, 21 seconds; total counts recorded: 2,414.

characteristics have been established, and the crystal now on order will be so optimized.

Mapping speed of the hybrid instrument is gratifyingly high. A number of clinical studies are presented in the following section, and it will be noted that scanning times are about one-half to one-fifth those typically required by a conventional rectilinear scanner.

RESULTS

Patient studies with the hybrid scanner were initiated in May, 1964, quite early in the development of the instrument. Accumulation of clinical experience has been rather slow, because of frequent redesign of the equipment as deficiencies became apparent; at present writing, only 28 patients have been scanned, although a number of these were seen on several occasions. Several clinical radioisotope maps are presented in Figs. 5-11 as examples of the studies which have been performed.

Figure 5 presents a PA brain scan on a patient injected four days previously with 800 μC of ^{131}I-labeled anti-fibrinogen antibody (11,12,13). A slow cot speed of one inch per minute was employed, and the map was completed in 9 minutes, 15 seconds. Approximately 18,000 counts were recorded. A metastatic tumor on the right side is reasonably well visualized. Figure 6 shows a right lateral view of this same patient, made immediately after the previous scan. The same speed was used, but less area was mapped, and the time required was only six minutes. The tumor is well delineated.

This patient exhibited excellent uptake of the antibody preparation in her tumor, and was therefore given a therapeutic injection of 110 mC of ^{131}I labeled antibody (14). A right lateral brain scan made 12 days after this injection is shown in Figure 7. Activity was still quite high, and the maximum cot speed of five inches per minute was used, allowing this scan to be completed in 90 seconds, during which period over 34,000 counts were recorded. Had a higher speed been available, a satisfactory map could have been produced in even less time.

This same patient returned again 33 days following her therapy injection, at which time some activity still remained bound in the tumor, but blood and tissue activities had all but disappeared. Figure 8 presents a right lateral scan made at this time; 3 minutes and 21 seconds were required for this view, which contained only about 2,400 counts. The fact that the tumor is quite well delineated in spite of this small number of counts is due to the extremely favorable target-to-nontarget specific activity ratio in this case. (The original films from which Fig. 8 was prepared are shown in Figure 4.)

In Figs. 9, 10 are seen PA views of the right and left lungs, respectively, of a subject given 250 μC of ^{131} I-labeled macroaggregated albumen (15), some two hours previously. The speed, long traverse, and easy access to the posterior aspect of the patient make the hybrid scanner particularly suited for this type of scan. The impaired vascular supply to the lower right lung is clearly visible. Each of these views was completed in exactly four minutes; approximately 7,500 counts were recorded from the right lung and 10,400 counts from the left.

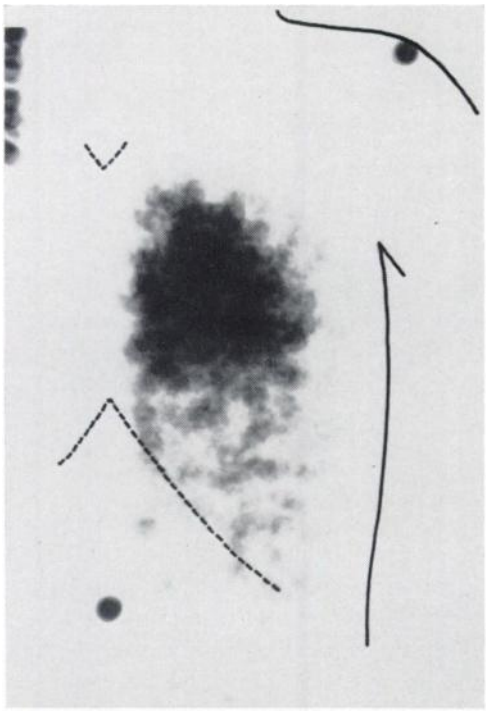

Fig. 9. A PA scan of the right lung of a patient given 250 μC of ^{131}I labeled macro-aggregated albumin two hours previously. Impaired vascularity of the lower right lung is well demonstrated. Mapping time: 4 minutes; total counts recorded: 7,513.

The anatomical landmarks shown in these two views were, of course, obtained on the uppermost anterior aspect of the patient, while the scans were made from the posterior aspect. The costal margin and supra-sternal notch were shown by dashed lines to indicate that these features are seen through the body.

Figure 11 presents the results of the only liver scan with colloidal ^{198}Au (16) which has been attempted to date. The patient was given 300 μC of this agent six hours before the study. She was unable to assume the prone position, and therefore was scanned from the posterior aspect. The scan was completed in 2 minutes and 36 seconds, with over 35,000 counts recorded.

DISCUSSION

The results presented in the preceding section demonstrate that the hybrid instrument is capable of producing scans of acceptable quality in reasonably short times. An entire study can be completed swiftly and with little patient discomfort.

The outstanding disadvantage of the present instrument is its limited scanning width. The entire head cannot be seen in a lateral brain scan, and the mapping of even moderately large areas requires multiple overlapping views, which tends to nullify any speed advantage over a standard scanner. This problem will be greatly reduced with the installation of a new crystal now on order. This detector will have a two inch by two inch square cross section, and will be 11 inches long. Allowing for anticipated nonlinearity at the extreme ends of the crystal, a

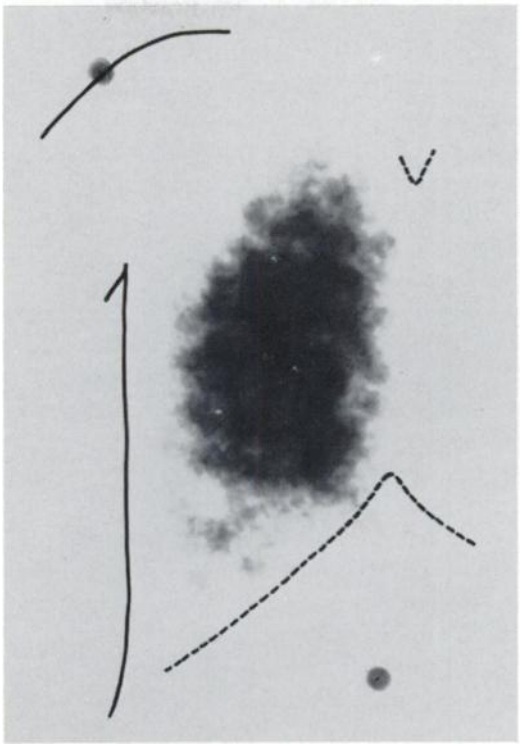

Fig. 10. A PA view of the left lung made immediately following the scan shown in Fig. 11. Mapping time: 4 minutes; total counts recorded: 10,361.

26 cm scanning width should be obtained. This width is adequate for the majority of studies, and will allow a considerable reduction in the number of views which must be made when large areas are to be mapped.

Other disadvantages of the present instrument which might be cited are the lack of any quantitative read-out other than the profile scan, and the placement of the detector below the subject. Also, the use of a stationary detector and moving subject arrangement precludes the use of standard hospital beds for scanning; thus, the handling of extremely fragile patients is difficult. However, these disadvantages are not fundamental, and may be overcome by redesign of the present device.

On the positive side, the combination of an electronically sensed transverse scan with a mechanical longitudinal scan results in a particularly uncomplicated instrument design. With but two multiplier phototubes involved in the scintillation position sensing system, alignment of the instrument is extraordinarily simple. Since the position signal is derived from the ratio of phototube pulses, size of the final display is independent of photon energy; also, efficient wide-window pulse height analysis of detector pulses may be employed. The scanning system is also relatively immune to fluctuations in phototube high voltage supply, and since the position signal is the logarithm of the voltage ratio, any gain shifts in one of the phototubes or amplifiers will result in a baseline shift of the display, but not in a nonlinear distortion of the map.

SUMMARY

A radioisotope mapping system intermediate in speed and complexity between a standard mechanical rectilinear scanner and a stationery camera-type device was developed in this laboratory. In this instrument, a scintillation position sensing system is used for the determination of activity distribution in one direction, while the complete area map is produced by a mechanical motion at right angles to this direction. Because of the combination of an electronically sensed transverse scan with a mechanical longitudinal scan, the instrument has been termed the hybrid scanner.

In this communication, the operating principle and design of the hybrid scanner are described, and performance characteristics of the instrument are discussed. Several clinical scans are presented, including a brain scan made in 90 seconds under unusually favorable conditions of high activity and high target-to-non-target specific activity ratio. The advantages and disadvantages of the present version of this instrument are discussed, and areas of potential improvement noted.

The hybrid scanner has proved to be extraordinarily simple to align and operate, and has produced radioisotope maps of satisfactory quality in about one-half to one-fifth of the time required for a conventional rectilinear scan. Experience gained with this instrument during development leads to considerable optimism that it will prove to be a useful addition to the array of radioisotope mapping instruments now available.

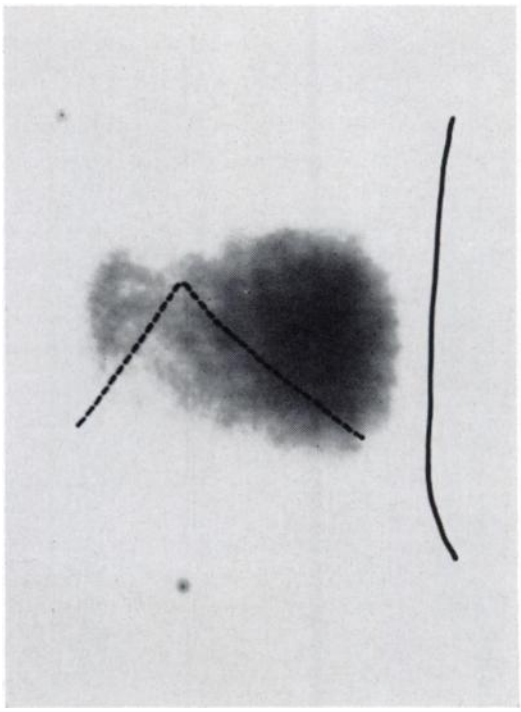

Fig. 11. A liver scan made from the posterior aspect on a patient given 300 μC of colloidal ^{198}Au six hours previously. This unusually small liver was covered by the 7.5 inch scanning width. Mapping time: 2 minutes, 36 seconds; total counts recorded: 35,103.

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