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Author
Anger, Hal O.

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Hal O. Anger
Donner Laboratory of Biophysics and Medical Physics
and Radiation Laboratory
University of California, Berkeley, California

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ABSTRACT

A new and more sensitive gamma-ray camera for visualizing sources of radioactivity is described. It consists of a lead shield with a pinhole aperture, a scintillating crystal viewed by a bank of photomultiplier tubes, a signal matrix circuit, and an oscilloscope with a scope camera. Scintillations that fall in a certain narrow range of brightness, such as the photopeak scintillations from a gamma-ray-emitting isotope, are reproduced as point flashes of light on the oscilloscope screen in approximately the same relative positions as the original scintillation in the crystal. A time exposure of the oscilloscope screen is taken with the scope camera, during which time a gamma-ray image of the subject is formed from the flashes that occur. One of many medical and industrial uses is described, namely the visualization of the thyroid gland with I^{131}.

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This paper describes an improved gamma-ray camera, previously described briefly,[1] which is much more sensitive than other gamma-ray cameras that have been reported.[2, 3] It employs a lead shield with a pinhole aperture through which gamma rays may enter, a large flat scintillating crystal within the shield viewed by a bank of seven photomultiplier tubes, a signal matrix circuit, a pulse-height selector, an oscilloscope, and a conventional camera to photograph the oscilloscope screen.

Briefly, the operation of the scintillation camera is as follows. Gamma rays are emitted from the subject, some of which travel through the aperture in the lead shield and continue traveling in straight lines until they impinge on the scintillating crystal. The light that is produced in any given scintillation is emitted isotropically and divides between all the phototubes, with those closest to a given scintillation receiving the most light. The duration of each scintillation is short compared with the average time interval between them.

The pulses obtained from the phototubes are applied to the signal matrix circuit, which adds and subtracts the amplitudes in such a way that three output signals are obtained. Two of the signals are positioning signals, which are applied to the X and Y input terminals of the oscilloscope. The third, or Z signal, is obtained by adding together the pulses from all the seven phototubes, with equal value being given to each. Then a scintillation of a given magnitude produces a Z signal of substantially the same magnitude regardless of where it originated in the crystal. This signal is applied to the input of the pulse-height selector and then to the intensity-input terminal of the oscilloscope.

When a scintillation occurs, the oscilloscope beam, which is blanked or extinguished at this time, is deflected by the X and Y signals to a point corresponding to the location of the original scintillation in the crystal. Then the beam is unblanked or turned on momentarily, provided the Z signal passes the pulse-height selector. The result is that scintillations in the crystal are reproduced as flashes on the oscilloscope screen at greatly increased brightness, with the provision that only scintillations falling within a narrow range of brightness are reproduced. They are displayed in approximately their original locations and the definition of the picture is not limited by the number of phototubes employed. In normal operation the pulse-height selector is adjusted to accept the photopeak pulses from a given gamma-ray-emitting isotope.

The flashes on the oscilloscope screen are photographed, usually by a Polaroid-Land camera which develops the picture within the camera in one minute. The exposure time may last from a few seconds to an hour or more. During this time an image is built up from the flashes that occur. If only a few are recorded, they appear as separate dots which are more numerous in the places of maximum activity. If many are photographed in one exposure and the camera lens is suitably adjusted, the dots merge together and show a gamma-ray image of the subject in shades of gray and white against a black background.

Among the advantages of the scintillation camera are the following. It is concurrently sensitive to all parts of its field of view, an advantage when rapidly changing activity patterns are studied. There is no line structure to the image, since scanning is not employed. An area of any size may be studied by moving the camera closer or further away. It can be readily oriented in any direction so that horizontal, vertical, and oblique views can be taken. It can be adjusted to be sensitive only to photopeak pulses of the isotope being studied, thus rejecting radiation scattered by adjacent objects or tissue. The sensitivity and definition are such that it is suitable for many medical and industrial uses.

Detailed Description

A sectional view of the camera is shown in Fig. 1. The camera housing is made of lead, and it shields the scintillating crystal on all sides except for the pinhole aperture through which the gamma rays enter. Above the aperture is the thallium-activated sodium iodide crystal, which is 4 inches in diameter and 1/4 inch thick. It is backed with magnesium oxide to reflect maximum light. A short distance above the crystal is the bank of seven 1.5-inch-diameter photomultiplier tubes. The tubes are spaced a minimum distance apart and the spaces between the photocathodes are covered by light reflecting surfaces. Some of the light-reflecting surfaces are painted white, and others are mirror surfaces. The space between the crystal and the phototubes is filled with a transparent optical fluid.

A diagram showing the paths of the signals after they leave the phototubes is in Fig. 2. The signal matrix circuit is shown with a block diagram of the other main parts of the electronic circuit.

The Y-axis positioning signal is obtained in the following way. The outputs from Phototubes 2 and 3 are fed through resistances R_{12} and R_{13} to one terminal of the Y-axis difference circuit, and the outputs from Phototubes 5 and 6 are fed through resistances R_{15} and R_{16} to the other terminal of the difference circuit. The four resistances are equal in value. The amplitudes of the two signals are then subtracted one from another to obtain the Y signal, which has an amplitude and polarity dependent upon the location along the Y axis of the scintillation in the crystal. The signal is amplified and is then shaped by means of a shorted delay line. The resulting pulse is about 1 microsecond long, and is rectangular in shape with a flat top. It is applied to the Y-axis input of the oscilloscope.

The X-axis signal is obtained in almost the same way as the Y signal. The outputs from phototubes 1, 2, and 6 are added through resistances R_{21}, R_{22}, and R_{26}. Here R_{21} and R_{26} are of equal value but R_{22} is one-half the value of the others. This is necessary because Phototube 1 has twice the linear displacement along the X axis of the other two phototubes. The outputs of Phototubes 3, 4, and 5 are also added through resistances R_{23}, R_{24}, and R_{25}. The value of R_{24} is half the value of the others. The signals are applied to the two terminals of the X-axis difference circuit,

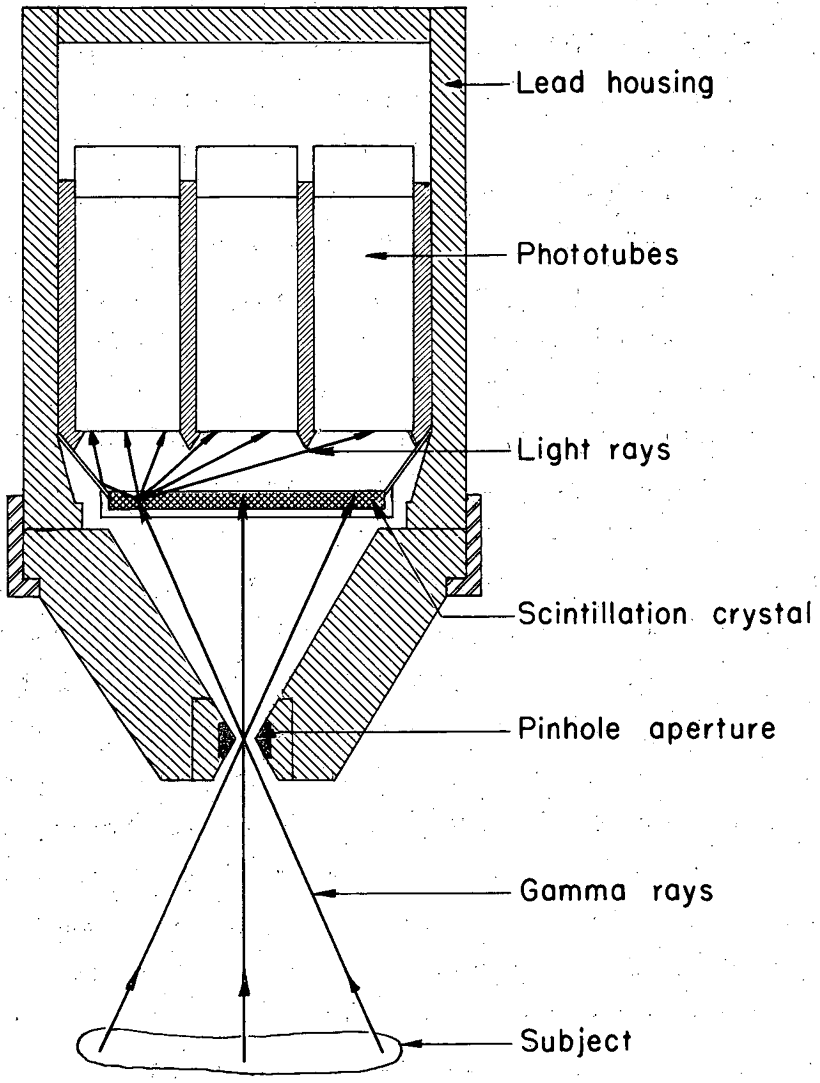

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Fig. 1. Sectional drawing of scintillation camera.

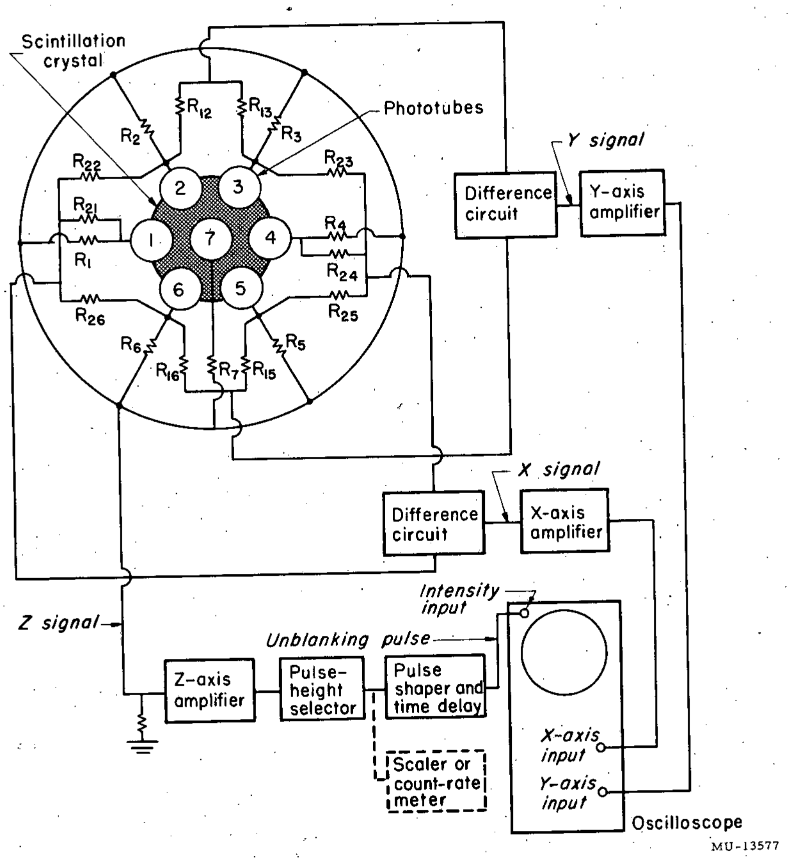

Fig. 2. Block diagram of electronic circuit.

and the resulting output signal is amplified and shaped in the same way as the Y signal. The amplitude and polarity of this signal depend on the location of the scintillation along the X axis. It is applied to the X input of the oscilloscope.

The Z signal is obtained by adding the outputs of all the phototubes through resistances $R_1 - R_7$, all of which are of equal value. The resulting signal is amplified and fed to the input of the pulse-height selector. The output signal goes to a pulse shaper and delay circuit, which shortens the pulses and delays them so that the oscilloscope beam is unblanked only at the peak of the excursion caused by the X and Y positioning signals. This signal, called the unblanking pulse, is applied to the intensity input of the cathode-ray oscilloscope.

Adjustment and Operation

The operation of the camera depends upon the phototubes all being equally sensitive to light. They can be adjusted to meet this condition quite easily in the following way. A sample of the gamma-emitting isotope to be used is first placed inside the camera near the pinhole aperture so that the entire scintillating crystal is irradiated with gamma rays. The pulse-height selection window is set to a fixed height and the width is set to about 10% of the height. Then the phototube supply voltage is increased from below the threshold voltage until a maximum number of flashes appears on the screen. Then, by adjustment of the individual phototube voltages, the pattern on the screen is made symmetrical about the origin and evenly illuminated. The voltages on Phototubes 1 — 6 are adjusted for equal maximum deflection from the origin, and the voltage on the center phototube is adjusted for the most even distribution of the flashes radially over the screen.

After the pattern has been made symmetrical, the supply voltage is usually readjusted for maximum counting rate from the photopeak portion of the pulse-height spectrum. The pulse-height selector will then be accepting pulses from photopeak scintillations that occur anywhere in the crystal. The window width is set to the minimum value at which most of the pulses within the photopeak are passed. This results in the clearest picture and the lowest background.

Normally, the camera is set to the photopeak, as described above, because the counting efficiency is then relatively high and scattered radiation is rejected. However, it is also possible to set it to a portion of the

Compton spectrum. This may be desirable for viewing a source that contains a mixture of isotopes of different energy.

Factors Affecting Resolution

A list of the major factors affecting definition include: The pinhole aperture size and the distances between the aperture, subject and scintillator; statistical variations in the distribution of the scintillation photons among the phototubes, the production of electrons at the photocathodes, and their subsequent multiplication; the width of the pulse-height selector window; and mislocation of the flash on the oscilloscope screen when a single gamma ray produces first a Compton recoil and then a photoelectric recoil in the scintillating crystal. In addition, the definition of any given picture depends on the number of counts or dots contained in it. This is a function of subject activity and exposure time as well as of the aperture size and the distances involved.

The resolution obtained with four different aperture sizes is shown in Fig. 3. The test pattern consisted of 12 small sources of I^{131} arranged in a square array with two sources each in the top and bottom rows and four each in the others. The exposure time was varied so that an equal number of counts was recorded with each aperture. The 1/8-, 3/16-, and 1/4-inch apertures are made of platinum, because of its relatively high stopping power for gamma rays, although tungsten would have been almost as good. The 5/16-inch aperture was made of lead. The definition is shown to be progressively better as the aperture size is decreased. The geometric factors are relatively straightforward, but they are complicated by the fact that the effective aperture size is somewhat larger than the actual size because some of the gamma rays go through the edge of the aperture. This effect is reduced by the use of a very dense material for the aperture, such as platinum or tungsten. When the camera is adjusted to the photopeak gamma rays that are scattered through a wide angle by the aperture are eliminated by the pulse-height selector, since they have been degraded in energy. However, the few gamma rays that happen to be scattered through only a small angle are not rejected if the change in their energy is very small.

Regarding the statistics of photon distribution and of photoelectron production, a photoelectric recoil of the 0.36-Mev gamma ray of I^{131} produces

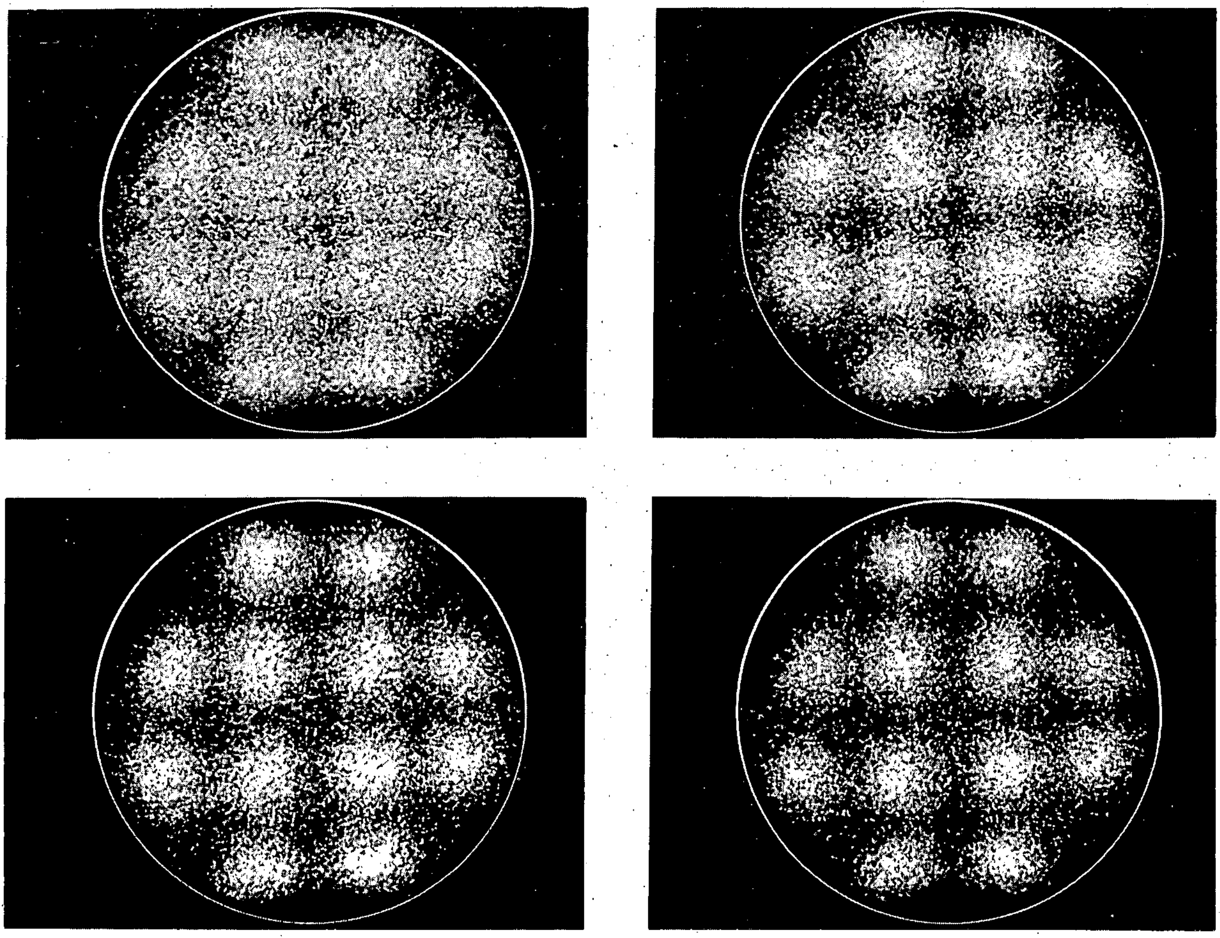

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Fig. 3. Scintillation pictures taken with apertures of 5/16, 1/4, 3/16, and 1/8 inch diameter. The test pattern consisted of 12 small sources of I^{131}.

about 4000 to 5000 photons that reach the phototubes, and about 300 to 400 photoelectrons[4] are produced at the photocathodes. If a scintillation occurs at the center of the crystal, each of the edge phototubes receives about 12% of the light. This has been determined by measuring the pulse heights obtained when a collimated beam of I^{131} gamma rays is directed to the center of the crystal. Therefore, about 40 photoelectrons are produced in each of the edge phototubes. The statistical variation in the positioning signals then corresponds to an uncertainty of about 1/4 inch in the scintillating crystal, a figure which agrees approximately with that obtained in practice.

The pulse-height selector window width should not be greater than necessary to pass most of the photopeak pulses, for the background due to stray gamma rays and cosmic rays would then be larger than necessary. Also, scintillations of greater or less energy than those desired could appear on the oscilloscope screen and the X- and Y-positioning signal magnitudes would not be correct for them. The effect would be similar to superimposing images of varying magnification, one upon the other, producing an astigmatic blurring at the edge of the picture.

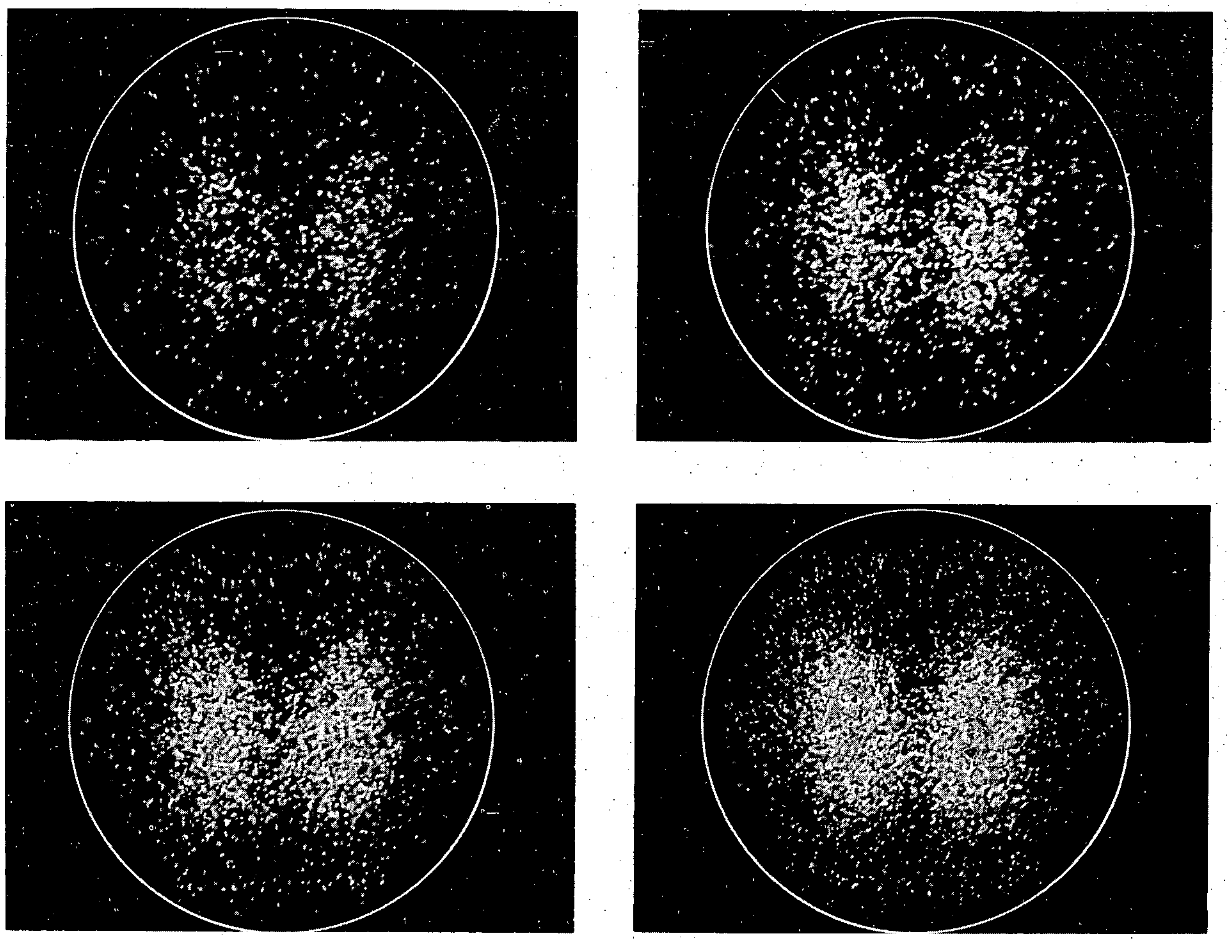
When a gamma ray produces a scintillation by the Compton process and the secondary gamma ray reacts again with the crystal to produce another scintillation by the photoelectric process, the light from the two scintillations, when added together, is the same as that which would be produced if the original gamma ray had produced a photoelectric recoil. Therefore, the signal produced passes the pulse-height selector but the positioning signals place the flash at some point intermediate between the two scintillations. Since only the original scintillation is at the correct site, the flash is misplaced. Fortunately this is a fairly rare occurrence, since most secondary gamma rays produced in Compton interactions escape from the scintillator without producing a second reaction. When they do undergo a secondary photoelectric reaction, the second recoil is usually a considerable distance from the first, and the net effect is only to produce a slight increase in background over a large area around the subject. Furthermore, if the second reaction is another Compton recoil, and the gamma ray then escapes, the light produced does no add up to the necessary amount, and the signal does not pass the pulse-height selector--provided the escaping gamma ray carries off sufficient energy. Multiple scintillations such as these are probably a limiting factor on the thickness of crystal that can be employed.

In Fig. 4 is shown the effect of the number of counts or dots on the appearance of the image. The number of counts is, of course, a function of subject activity, exposure time, and aperture size. The same test pattern is shown with 800, 1,600, 3,200 and 6,400 counts comprising the image. The increase in clarity of the image with an increasing number of counts is apparent. The subject in this case is a phantom thyroid consisting of a radioactive solution contained in a lucite form. Each lobe was elliptical in shape and of constant activity per unit area. The phantom contained 5 microcuries of I^{131} and was covered with 3/4 inch of lucite to represent overlying tissue. The exposure times for the four pictures were 5, 10, 20, and 40 minutes, respectively. The aperture size was 1/4 inch, and the distance between the aperture and the phantom was 5 inches.

Sensitivity and Distortion

The sensitivity of the present camera is such that about 10% of the 0.365-Mev gamma rays of I^{131} that impinge on the scintillating crystal, produce a photoelectric recoil. The background is about 30 counts per minute. Of the remainder of the gamma rays, 75% pass through the crystal without producing any scintillation at all, and 15% produce Compton recoils,[5] which are not normally reproduced on the oscilloscope screen. The sensitivity can probably be increased by the use of a thicker crystal, or by revising the electronic circuit so that Compton recoils are shown as well as photoelectric recoils. However, showing Compton recoils would have the disadvantage that radiation scattered in the subject and the aperture would not be rejected.

If a small radioactive source is placed at the geometric center of the pinhole aperture, and a picture is taken with the entire scintillating crystal evenly illuminated by I^{131} gamma rays, some distortion of the pattern is evident. Ideally the image should be a round, evenly illuminated disc, since the scintillating crystal is round. Instead the pattern is a rounded hexagon, with the six points on the circumference corresponding to the six radial phototubes. Also, a few more of the counts are concentrated near the border of the pattern than over the remainder of the area. The distortion can be decreased if the distance between the scintillator and phototubes is increased, but



ZN-1737

Fig. 4. Scintillation pictures taken of a thyroid phantom containing 5 microcuries of I^{131}.

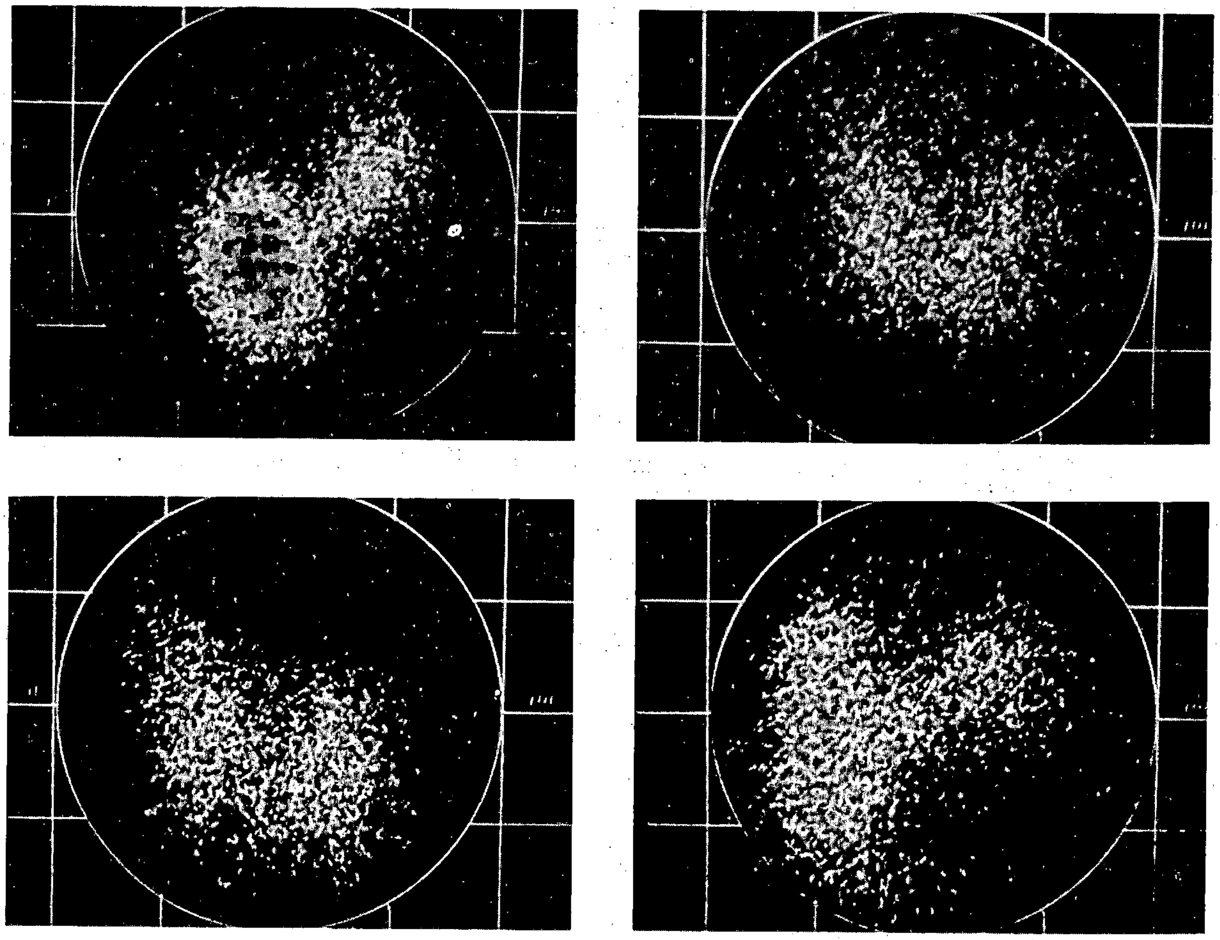
the definition decreases at the same time owing to the change in the distribution of light among the phototubes. Therefore, a compromise must be made between definition and distortion. With the configuration chosen, the distortion is negligible for most purposes, as shown by the approximately regular spacing of the test pattern image in Fig. 3. The distortion is confined almost entirely to the edges of the picture and is absent for all practical purposes from the central area.

It is possible to obtain an image by employing a multichannel collimator between the subject and the scintillating crystal instead of the pinhole aperture. The collimator consists of a plate made of lead or other dense material with many regularly spaced parallel holes. The area covered by the holes corresponds to the area of the crystal. For best definition and sensitivity, the subject should be as close to the multicollimator plate as possible.

It has been found, however, that when the plate is made of lead, and the hole sizes and spacing are optimum for I^{131} gamma rays, the hole structure is so coarse that the shape of the image is appreciably distorted by the collimator structure. If the plate were made of tungsten, the hole structure might be refined to the point where this would no longer be true. The distortion could, of course, be eliminated if the collimator were continually moved in the manner of a Bucky x-ray filter during the exposure time. Appreciably higher sensitivity might be obtained in this way. The holes in the plate could be parallel or angled inward or outward to view subjects smaller or larger than the scintillating crystal.

Thyroid Mapping

In Fig. 5 are shown a few examples of in-vivo pictures of the human thyroid gland taken with the scintillation camera. The amount of I^{131} in the gland varied from 7.5 to 12.5 microcuries, and the exposure times varied from 12 to 15 minutes. In all cases a 1/4-inch-diameter platinum pinhole aperture was used, and the distance from the aperture to the thyroid gland was about 5 inches. It is evident that the definition is adequate at the present time for thyroid mapping, and the amount of I^{131} required in the gland is quite low. Pictures could be taken with half the amount of I^{131} if the exposure time were doubled, or conversely pictures could be taken in half the time if



ZN-1738

Fig. 5. In vivo pictures of the human thyroid.

the I^{131} dose were doubled. However, no fixed relation between activity and exposure time must be maintained, because the picture quality improves with increasing activity in the gland and increasing exposure time.

If any abnormal uptake of I^{131} is suspected in a patient, a picture is usually taken with the scintillation camera at an increased distance from the subject and directed to the thyroid area. Then, the field of view is quite large, and if there is any substernal or upper cervical uptake, or any active nodule at some distance from the thyroid, it will be shown. A relatively large aperture and short exposure are used for this view, since the object is not to show detail, but to show the location of any abnormal uptake. Then the large aperture is replaced with a smaller one and the camera is moved closer to take longer, more detailed exposures of the thyroid and other points of uptake.

The amount of I^{131} present in the thyroid can be determined at the time a picture is taken by recording the number of pulses per unit time that pass the pulse-height selector with a scaler or count-rate meter. A more accurate measurement can be made by moving the camera back from the patient to minimize the error due to variation in the depth of the thyroid under the skin. It then functions as a regular directional scintillation counter with pulse-height selector.

Conclusion

There are many industrial uses to which the scintillation camera might be put, such as mapping areas of contamination, and following the movement of gamma-ray-emitting isotopes through industrial processes. The size of the area viewed can be large or small, depending on its distance from the camera, and remote viewing and recording are quite feasible. In cases where large amounts of radioactivity can be used, the oscilloscope screen can be viewed directly to see an image of the source, or motion pictures can be taken. An image-memory tube could be used to integrate and retain an image for visual observation. When the patterns of activity are changing, a series of short exposures or one integrated time exposure may be taken. Time-lapse motion picture techniques could be used to visualize slow action. The motion of radioactive tracers in plants as well as in animals could be studied in this way.

Future development of the camera will probably improve both the definition and sensitivity. The sensitivity may be increased by use of a thicker and larger scintillator, or perhaps by displaying Compton, as well as photoelectric, recoils. The background, although it is not high can be further reduced by use of a thicker camera housing. The definition may be increased if phototubes of increased sensitivity become available, by using an increased number of phototubes, or perhaps by improvement of the optical coupling between the scintillator and the phototubes.

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