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THE GAMMA-RAY PINHOLE CAMERA WITH IMAGE AMPLIFIER

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ABSTRACT

The gamma-ray pinhole camera is an instrument that can be used to determine the distribution of radioactive isotopes in vivo. To increase the sensitivity of the camera, a special gamma-detecting image screen was developed. This consisted of a lattice of sodium iodide crystals adjacent to the photocathode of an electronic image-intensifier tube. The absorption of the gamma image in the lattice results in a corresponding visible-light image with a resulting increase in the number of photons. This visible image is then intensified by the electronic image-intensifier tube. With this instrument it is possible to view directly the image of a gamma-emitting source, although a relatively strong source is required. Photographic integration of the final image allows detection of weaker sources. The ultimate sensitivity, limited by the background of the image intensifier tube, is in the order of 1 to 10 $\mu c/cm^2$. It is possible to resolve sources separated by no less than 1/4 in. Possible applications of the instrument as well as future developments along this line are discussed.

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INTRODUCTION

The well-known principle of the pinhole camera was applied to penetrating radiations as early as 1896 when Roentgen[1] used a pinhole in a piece of metal to obtain an image of the x-ray-emitting anode in one of his first tubes. More recently, Copeland and Benjamin[2] demonstrated the usefulness of a pinhole camera constructed of lead for obtaining images of gamma-ray emitters. Anger[3] in this laboratory has applied a similar instrument for demonstration in vivo of the distribution of radioactive iodine administered to a patient with thyroid carcinoma metastasis.

It would be of obvious interest in tracer turnover studies and in medical diagnostic work to have devices that would show the accurate in vivo distribution of radioactive substances in form of visual images, at a level where the administered dose of radioactivity would have negligible biological effect. In the two previous reports on the application of pinhole cameras to this problem, very large amounts of activity were necessary to obtain a final photographic image, even when a sensitizing screen of sodium iodide crystal was placed in front of the photographic film[3]. Scanning devices employing scintillation counters with associated directional apertures have been applied with success to this problem[4,5,6,7]. However, this system does have the disadvantage of requiring a period of scanning in order to obtain a final image, thus reducing its applicability to studies involving dynamic systems. The pinhole camera arrangement continuously produces an image of the object being viewed. Thus, any motion or changes in activity of the object are readily detectable.

In this paper, a method of increasing the sensitivity of the pinhole camera apparatus is described. It is accomplished in two steps. Firstly, the gamma-ray image is converted to a visible light image in a lattice of thallium-activated sodium iodide crystals. The image from the crystal lattice then falls directly onto the photocathode of an electronic image-intensifier tube. The conversion of the gamma-ray image to a visible light image in the crystal lattice results in a thousandfold increase in the photon flux. The image-amplifier step produces an additional 600x increase in image brightness. The over all amplification has made it possible to view directly sources whose activity is in the range of 200 $\mu c/cm^2$ or greater. Although this activity is still much larger than usually encountered in biological and medical systems, we feel that with development of more sensitive image pickup tubes it may be possible to view directly the gamma-ray distribution in a patient who has received a relatively small dose of radioactivity. These developments would be of considerable value for diagnosis of cancer, wherein a radioactive isotope is localized selectively in a tumour.

APPARATUS

1. Construction of the Camera

Walls and Pinhole. The high penetrability of gamma radiation imposes certain problems in the construction of the walls and pinhole of the camera. The ideal situation would occur if there were 100% transmission through the pinhole and no transmission through the walls. This of course can only be approximated, owing to the exponential absorption processes of gamma radiation. Table I presents values of wall thicknesses for different energies of gamma radiation necessary to reduce the intensity to one-half its original value, and also to 1% of its original value. The latter column might be considered as a satisfactory as well as practical thickness of wall material.

TABLE I

Gamma Energy (Mev)	Half-value thickness cm Pb	1% thickness cm Pb
0.10	0.015	0.097
0.20	0.066	0.43
0.50	0.31	2.0
1.0	0.77	5.0
1.5	1.12	7.3
2.0	1.40	9.1
3.0	1.45	9.5

Copeland and Benjamin[2] have given considerable attention to the design and construction of suitable pinholes for this type of camera. The pinhole used in the apparatus discussed here is quite similar to one they have described. Figure 1 is a drawing of a cross section through the pinhole. The relatively small angular opening (60°) is necessary to obtain sufficient absorption of the gamma radiation adjacent to the pinhole. It is still large enough to permit a practical angle of acceptance. The penetration by the gamma photons of the wall material surrounding the pinhole results in an effective increase in the diameter of the pinhole. This increase as shown in Table II is a function of the gamma energy, being larger for higher-energy gamma photons.

TABLE II

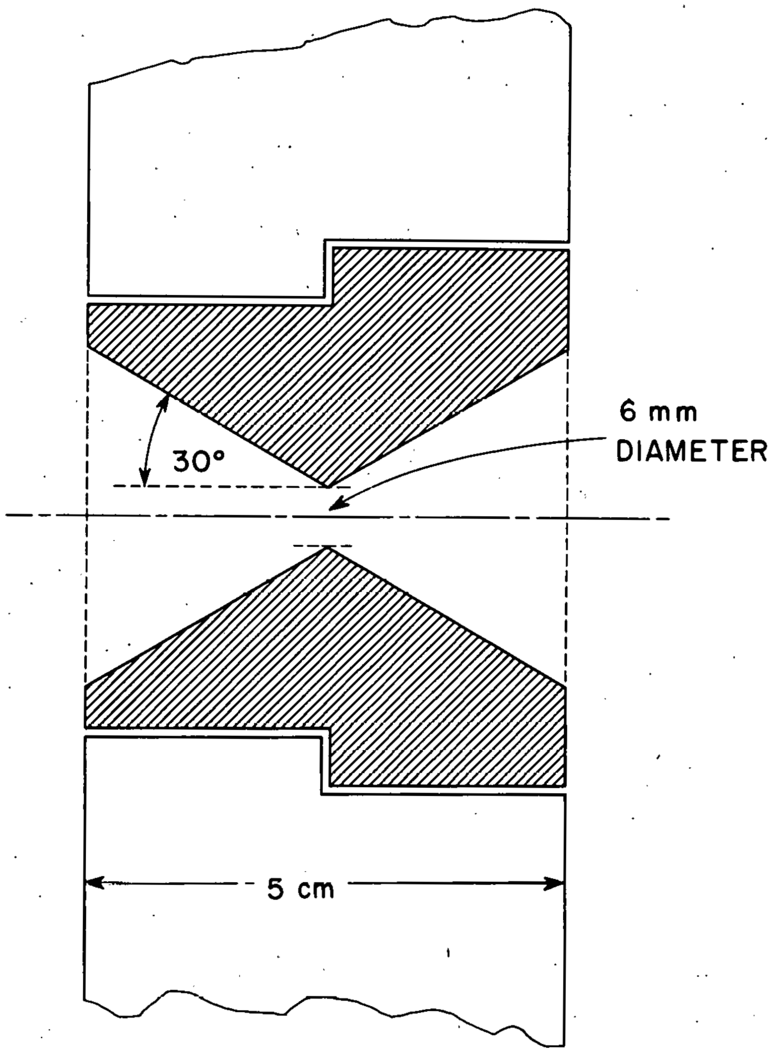
Transparency of a Lead Pinhole to Gamma Rays

Gamma Energy (Mev)	$\delta_{cm.}$ *	Effective Diam. (cm) for a 5 mm opening = d + δ
0.1	0.0096	0.51
0.2	0.056	0.56
0.5	0.26	0.76
1.0	0.64	1.14
1.5	0.92	1.42
2.0	1.15	1.65
3.0	1.19	1.69

* $\delta = \frac{1}{\mu} \tan \alpha =$ increase in diameter necessary to reduce the intensity to 1/e

μ = absorption coefficient (cm^{-1})
α = half apex angle = 30°
d = diameter of opening

This increase in effective diameter of the pinhole influences the ultimate resolution obtainable with the camera. The details of this effect are considered in a following section.



CROSS SECTION OF PINHOLE

Fig. 1

2. Gamma-Sensitive Screen

The gamma-sensitive screen consists of two principal components (Fig. 2), a crystal lattice which serves to convert the absorbed gamma-ray energy into visible light quanta with an effective increase in the number of quanta, and an electronic image-intensifier tube which then intensifies the image emitted from the crystal lattice. These two components are here described in more detail.

Crystal Lattice. In the earlier paper by Anger[3], a gamma-sensitive screen is described which utilizes a large slab (2 x 4 x 5/16 inch) of thallium-activated sodium iodide crystal to convert the gamma energy to visible light. The isotropic emission of visible light from the point of absorption in the crystal results in a loss in resolution. Resolution is also lost as a result of the multiple internal reflections. These effects could be reduced by using thinner crystal slabs, but not without loss in sensitivity. These difficulties were partially avoided in the present apparatus through use of a lattice of individual crystals (1/4 in. D x 1/2 in. L) mounted in such a fashion that the crystals were optically isolated from one another. Thus scattering and subsequent loss of resolution would be limited to the size of the individual crystal elements. The crystals used were again thallium-activated sodium iodide, these being selected because of their relatively high absorption coefficient for gamma rays as well as the relatively high yield of visible quanta ($> 10^4$/mev absorbed gamma energy[8]). The crystals were mounted in a hexagonal matrix of holes drilled in an aluminum holder. The walls of the holes were painted with white Tygon paint to permit maximum transmission of the isotropically emitted light through the end of the crystal facing the photocathode. The crystals were mounted in Aroclor to protect them from the atmospheric moisture. This mounting medium has nearly 100% transmission for the wavelengths emitted by these crystals (maximum 4100Å; half width 800Å). In addition, the sensitivity of the photocathode of the image amplifier tube has a maximum at 4300Å, which is near the maximum output of the crystals. The crystal lattice was 5-1/2 in. in diameter and contained 241 crystals, there being 17 picture elements across a diameter of the lattice. The shape of the aluminum holder was designed so that it would fit directly over the photocathode end of the image amplifier tube, thus providing direct optical contact between the crystal lattice and the photocathode.

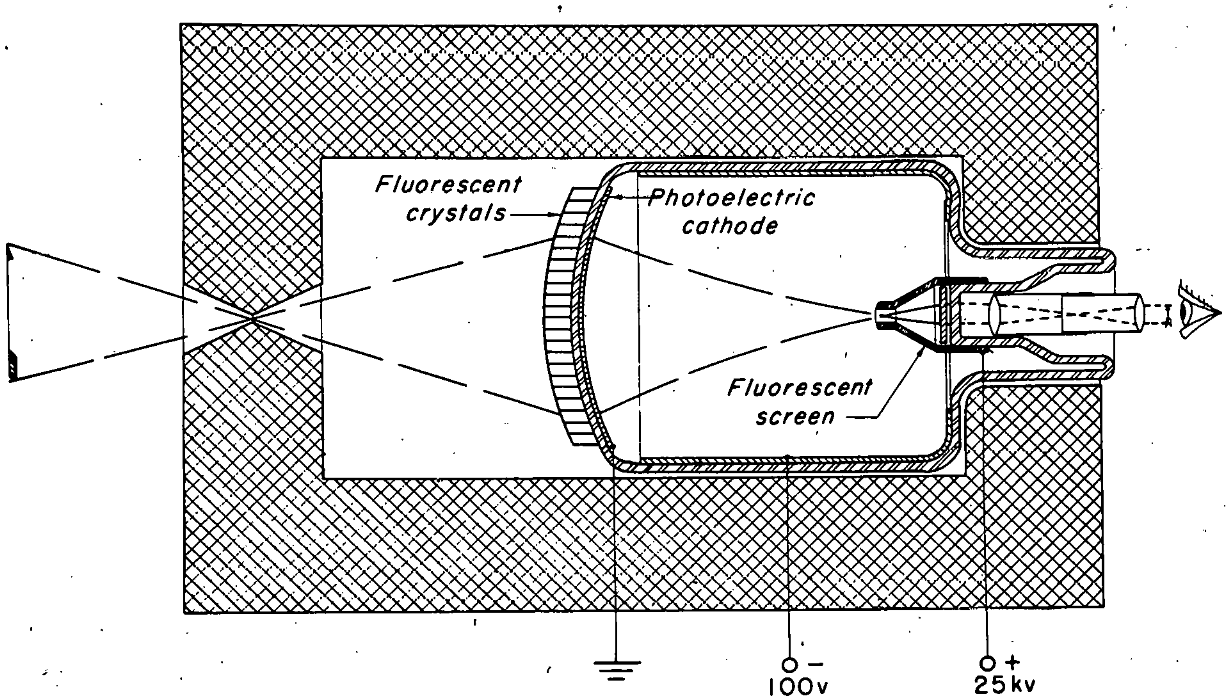

Fluorescent crystals
Photoelectric cathode
Fluorescent screen
100v
25kv

Fig. 2

<u>Image Amplifier Tube.</u> The image from the crystal lattice was intensified with an electronic image-intensifier tube similar to the type used in fluoroscopy. The tube was obtained from the Philips Research Laboratories[9*]. The ZnS screen normally present on image-amplifier tubes used in fluoroscopy was absent, the first stage being the photocathode. The image falling on the photocathode produces an "electronic image" from the photoelectric surface. These electrons are then accelerated by a potential of 25 kv through an electron lens system and strike an image screen of zinc sulfide-zinc selenide crystals. The size of the final image is only 1/9 that of the photocathode, and it can be viewed directly or through a magnifying lens system. The intensification of the image results both from the reduction in image size and from the increase in light yield arising from the acceleration of the photoelectrons. The tube intensifies the image by a factor of about 600. It has a fairly high background, owing to both thermal and field emission of electrons from the photoelectric surface. A combination of cooling the tube to 0° C and lowering the voltage reduces the background by a large factor (~10x) without too much loss in amplification. However, the background even under these conditions limits the sensitivity to objects whose activities are greater than $\sim 10\ \mu c/cm^2$.

<u>Resolution and Sensitivity</u>

As in most optical systems, resolution and sensitivity are interdependent, resolution being gained only at the sacrifice of sensitivity. For a source-to-pinhole distance a, pinhole-to-screen distance b, and effective pinhole diameter d, the minimum distance s by which two point sources can be separated and still be resolved is:

$$s = \left(\frac{a + b}{b}\right) d .$$

This formula is effective except for values of a, b, and s that lead to a separation of the two images formed on the detecting screen which is less than the distance between the detecting elements (0.300 in.). It can be seen from examination of Table II, that the dependence of effective pinhole diameter on the gamma-photon energy also imposes a limit on the ultimate resolution.

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* We are indebted to Dr. Oosterkamp of the Philipses' Gloeilampenfabrieken in Eindhoven for agreeing to construct this special tube for us.

The brightness of the final image is proportional to the flux of gamma radiation striking the crystal lattice. This is given by the formula:

$$N = \frac{3.7 \times 10^4 \sigma d^2}{16 b^2}$$

where N = number of gamma photons/cm^2/sec on the screen

σ = surface density of activity of the source $\mu c/cm^2$.

It can be seen that the sensitivity is independent of the distance of the object from the camera, a feature not present on parallel-aperture scanning devices.

RESULTS

The apparatus herein described has been used to produce images of gamma-emitting objects of known dimensions and activity in order that its sensitivity and resolution could be checked. The results obtained in these experiments were very encouraging, as far as the basic principles of the instrument are concerned. Clear images of gamma-emitting objects were formed, and these could be viewed directly on the final image screen. The resolution, too, was quite good; it was possible to resolve two sources separated by about 1/4 in. when the sources were 3 in. from the pinhole. Motions of the source were readily detectable, thus demonstrating the value of this type of instrument in dynamic studies. However, the sensitivity for direct visualization was limited to sources whose activity was greater than about 200 $\mu c/cm^2$. This surface density of activity is still in excess of that normally encountered in biological and medical experiments involving the use of radioisotopes. For cases where more activity can be used or where larger x- or gamma-ray fluxes are available, the instrument in its present form can be of considerable value. Applications may be in nondestructive testing of materials in the field of engineering, or in general scanning of areas for large amounts of radioactivity.

Photographic integration of the image formed on the final screen of the image-amplifier tube has little advantage over direct-contact photography of the visual image produced in the crystal lattice. This is because the position of the final screen necessitates use of a lens system to obtain an image on a photographic film, and a two-hundred-fold loss in light quanta is involved.

A photograph of the image formed on the final screen is shown in Fig. 3. The object was in the shape of a V 2 in. high by 1-1/2 in. wide by 1/4 in. The object-to-pinhole distance was 9 cm; pinhole-to-screen distance 15 cm; pinhole diameter 3 mm; and the surface density of activity of the source was 4 mc/cm^2. The exposure time using Super-XX film was 8 min.

DISCUSSION

With the present pinhole camera a significant amplification of image brightness was obtained, making it possible to view gamma-emitting radioactive sources directly. With the development of more sensitive gamma-detecting systems, it should be possible to use this principle in the diagnosis of cancer or in studies on dynamics in biological systems. Perhaps the most promising development in this direction may be along the line followed by Morton[10] and his group at RCA. They have developed a high-gain multiple-stage light-amplifier tube, and in addition have incorporated into the tube an image orthicon to pick up and reproduce the final electron image on a television system. Each secondary electron produced by the absorption of a gamma photon in the crystal lattice will cause the emission of about 10^3 photons. If the system is sensitive enough to record this number of photons in the form of a video signal, then theoretically it should have no basic limitations except for the background of the photoelectric surfaces in the system. One can calculate that with a 10^3 gain in photoelectrons obtained through the incorporation of multiple image-intensifier stages, there will be a sufficient number of electrons produced on the final stage to cause a detectable change in voltage on the image orthicon target. This then would result in a signal from a single gamma photon that could be recorded on a television system. Integration of the image could be obtained by using a television memory system. It should be possible to reduce the thermal background noise by biasing the video amplifier to exclude weaker signals coming from the thermal electrons.

Another approach might involve the use of a parallel-plate Geiger counter in conjunction with a suitable converting screen. This approach has already been shown by Lion[11] to provide a hundredfold increase in sensitivity for x-rays.

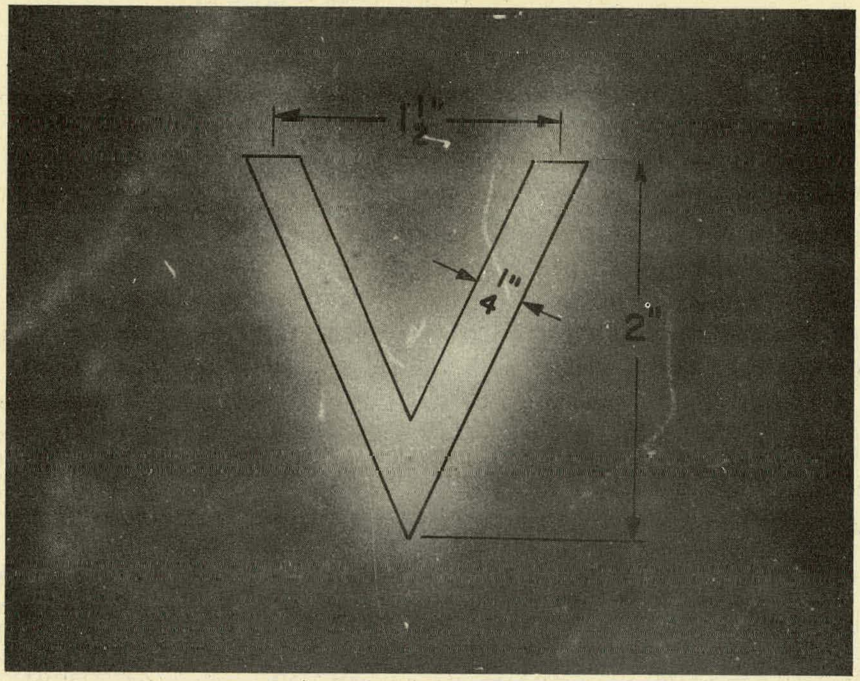

Fig. 3

Another gamma-detecting screen that would have a high sensitivity might consist of a lattice of individual crystals, each with an associated miniature photomultiplier tube. The signals from the lattice of photomultiplier tubes could then be used to produce an image that could be visualized or recorded photographically.

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