INITIAL CLINICAL EXPERIENCES WITH A FRESNEL ZONE-PLATE IMAGER

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First clinical studies with a Fresnel zone-plate radioisotope imager demonstrate high resolution, sharp tomography, and freedom from scatter. Improved radionuclide imaging is demonstrated, at least for small organs like the thyroid. Certain limitations are present that indicate a need for additional development before application to routine clinical practice.

Collimators impart the necessary position information to the usual radioisotope imaging systems. Such collimators reject all but the events arising from a very narrow solid angle. A novel approach to radioisotope imaging in which the collimator is replaced by a Fresnel zone plate has been recently described (*1–5*). Each radioactive point in front of the zone plate casts a unique shadow of the zone plate onto the detector (Fig. 1). The zone plate, therefore, serves to encode on the detector position information arising from the object of interest. Points at different distances from the face of the zone plate cast shadows of different size. Therefore, tomographic information is recorded in the single-coded image that has properties analogous to an optical hologram.

This report presents some initial clinical experience with a Fresnel zone-plate imaging system.

MATERIALS AND METHODS

The imaging camera is illustrated in Fig. 2. In brief, it consists of an off-axis Fresnel zone plate constructed of concentric, alternately opaque (lead), and transparent (aluminum) zones. The requirement for keeping the zones thin limits the usefulness of the zone plate to maximum energies of about 200 keV (*4*). The detector used in this study was a standard x-ray film cassette with "Lightning Plus" (®E. I. DuPont Co.) intensifying screens and RP/R (® Eastman Kodak Co.) x-ray film. In addition to the zone plate and cassette, a halftone screen consisting of alternating parallel aluminum and lead bars is placed in front of the zone plate. The halftone screen (*6*) is required in order to image low-spatial frequencies with the off-axis zone plate.

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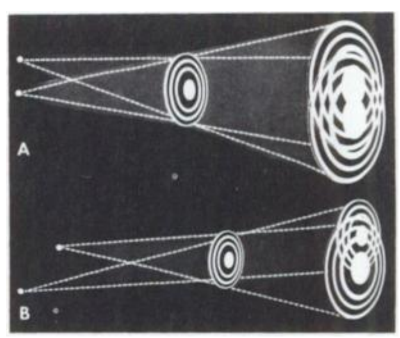

FIG. 1. Illustration of how position information is recorded by shadowing through zone plate. Lateral positions are recorded by displaced shadows on detector (A). Points at different distances from zone plate result in different size shadows (B).

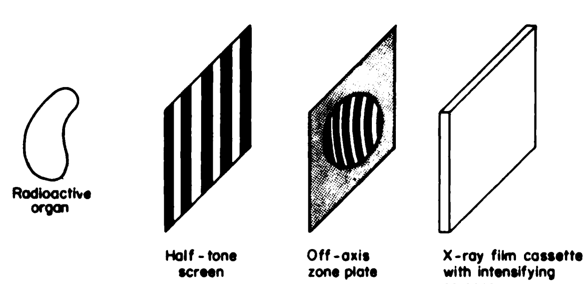

FIG. 2. Components of zone-plate camera.

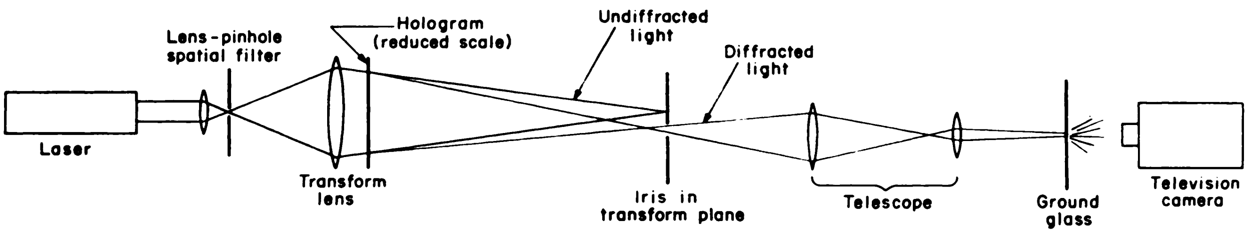

FIG. 3. Parts of optical reconstruction system.

The coded image formed on the developed x-ray film, analogous to an optical hologram, was copied onto a glass photographic plate with about a 20-to-1 reduction in size and placed in a coherent light beam (Fig. 3). The diffraction of light by the hologram produces an image that is viewed by a telescope. The image is tomographic. Movement of the "eyepiece" of the telescope allows focusing on different depths of the object reconstruction.

Patients referred for imaging procedures were selected to demonstrate some of the capabilities and properties of the system.

RESULTS

As the system has no scatter discrimination, phantom studies were performed to evaluate how severely the image is degraded by scatter. Figure 4 illustrates a planar object viewed 1 and 5 in. from the face of the camera through air and through water. The radioactive source is ^{57}Co. The zone-plate images are rather remarkably undisturbed by this degree of scatter. The same objects have been imaged with a Searle Radiographics Pho/Gamma III-HP scintillation camera with a high-resolution collimator (Fig. 5). The energy window was set to accept only the upper two-thirds of the photopeak. The results with the scintillation camera are somewhat less happy; there is less degradation of resolution in the zone-plate series. It should be noted that a planar phantom is the most favorable situation for both the scintillation and zone-plate cameras. In Fig. 6 the Picker thyroid phantom filled with ^{57}Co is imaged under 1 in. of water with 10 in. of water behind the phantom and again with a disk source of ten times the radioactivity at 4 in. and 2 in. behind the phantom. Observable degradation of the image is present in the latter situation but all four landmarks are clearly discernible.

A series of subjects and patients were studied to evaluate the clinical usefulness of the imaging system. Normal subjects took ^{123}I and both zone-plate and rectilinear scanner images were recorded. Each of the rectilinear thyroid scans have 1,000 counts/cm^2 at the point of maximum counting rate. Neither background subtraction nor contrast enhancement was used. The zone-plate thyroid images were made with

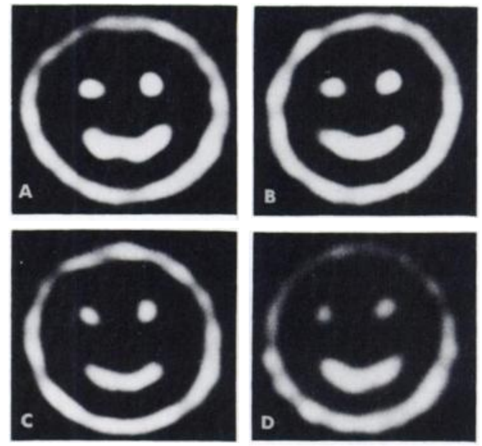

FIG. 4. Scatter effects on images made with zone-plate camera. Object is lead cutout transilluminated with ^{57}Co. Images at 1 in. (A and B) and 5 in. (C and D) from front of camera are compared both in air (A and C) and water (B and D).

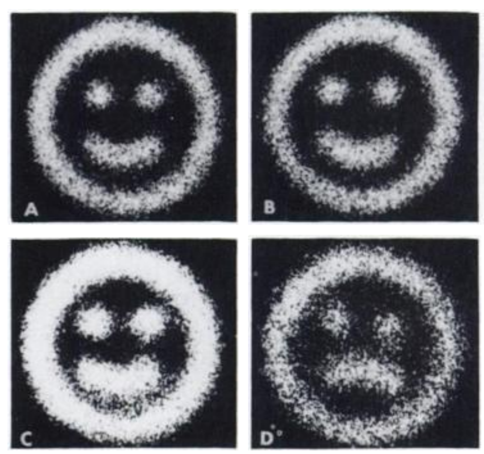

FIG. 5. Scatter degradation of scintillation camera images. Air and water comparison is same as in Fig. 4. D shows scatter by water; "mouth" has been justifiably inverted.

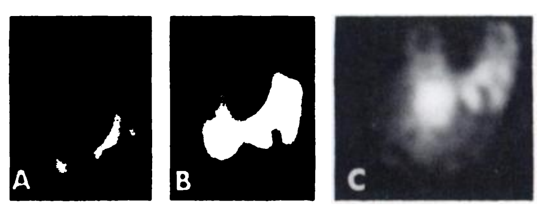

FIG. 6. Picker thyroid phantom filled with ^{57}Co is under 1 in. of water with 10 in. water behind (A). Same with ^{57}Co disk source of ten times activity 4 in. behind (B), and 2 in. behind (C). Under worst condition (C), all landmarks are discernible.

dose-exposure products of 20 mCi/min (v.i.). Figure 7 is of a normal man. The three anteroposterior planes shown are about 1.2 cm apart and were made from a single hologram by varying the focus of the telescope eyepiece in the reconstruction system. The changes from front to back are gradual and little structure is visible. Two patients with nodular thyroids of different etiologies are presented. A girl, euthyroid several years after partial thyroidectomy and 1 year after radioiodide treatment for recurrent hyperthyroidism, received ^{123}I for the study. The rectilinear scan and the zone-plate series (Fig. 8) equally define the right lobe remnants. The zone-plate reconstructions demonstrate an anterior "cold" nodule in the middle of the right lobe that most likely would remain unsuspected in the scan. Clinically, by palpation, there is an obvious nodule.

Another comparison from a patient with a large palpable nontoxic benign nodular goiter given ^{123}I (Fig. 9) demonstrates that the nodules, evident in the scan, are clearly visible and striking in the zone-plate series. Inherent contrast enhancement of the zone-plate imager (see Discussion) contributes to the clarity of definition.

Several larger organs were imaged with a zone-plate camera with a larger field of view (15 in. diam at 2 in. from the face) and comparisons were made with standard imagers. In Fig. 10 the images of a liver phantom filled with ^{99m}Tc demonstrate the value of the tomographic feature in ascertaining depth. Similarly, a clinical comparison (Fig. 11) shows agreement of the two techniques. A lung perfusion study (Fig. 12) of a patient with chronic obstructive pulmonary disease shows irregularities in the scintillation camera images that are striking in the zone-plate images.

A patient with a vertebral metastasis is shown in Fig. 13. Technetium-99m-polyphosphate was given. Focal uptake is evident in the rectilinear scan. The metastasis dominates the zone-plate series and even an overexposed copy gives little detail of the normal bone. The kidneys were not included in the zone plate's field of view.

Images of a dog heart with an acutely ligated left anterior descending artery are presented in Fig. 14. The animal was injected in the left atrium through an implanted cannula with ^{99m}Tc-macroaggregated albumin. Images were made in vivo through the open chest and on the excised heart. The auricle and atrial walls, the ventricular musculature, and the infarct are all clearly shown.

DISCUSSION

The clinical studies serve to demonstrate several features of the zone-plate system and indicate a po-

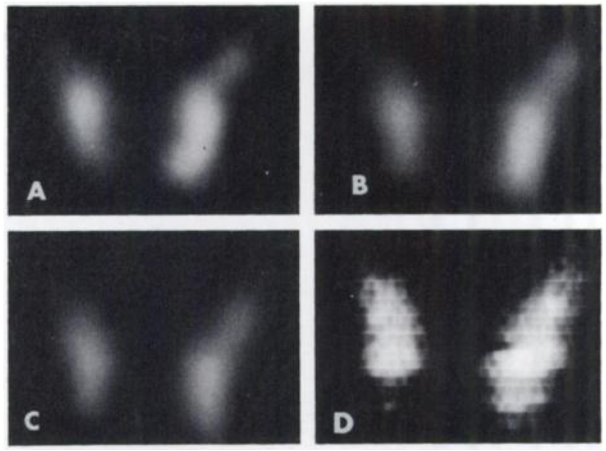

FIG. 7. Comparison of zone-plate and rectilinear normal thyroidal images. (A–C) are "cuts" from front, middle, and rear of the reconstruction encompassing less than 2 cm in total thickness (^{123}I). Bandlike area of reduced uptake in left upper lobe appears as narrowing when viewed on television monitor without discontinuities of reproductions.

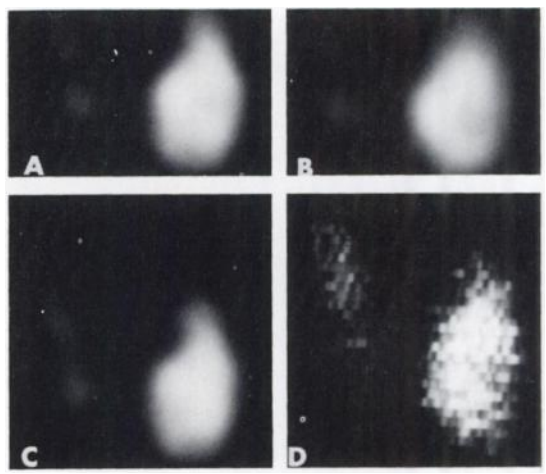

FIG. 8. After partial thyroidectomy and ^{131}I therapy. ^{123}I. Zone-plate series at 0.6-cm intervals (A–C). Nodule seen in B in zone-plate series is palpable but only suggested in rectilinear scan (D).

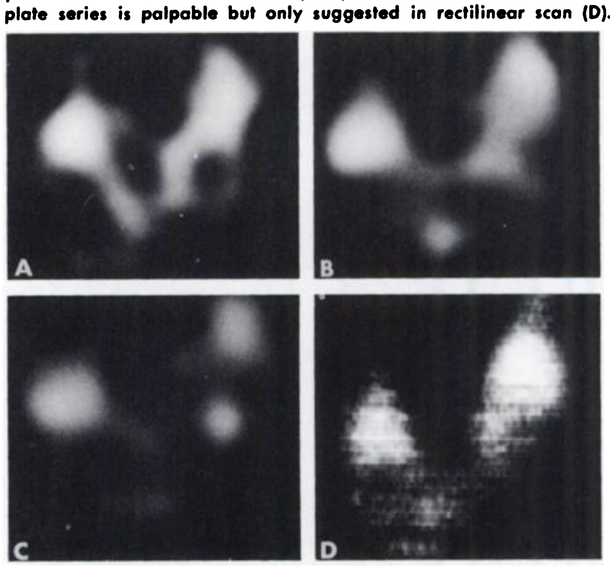

FIG. 9. Large multinodular nontoxic goiter. ^{123}I. Zone-plate series at 1.2-cm intervals (A–C). Whereas rectilinear scan (D) is diagnostic, zone-plate series more clearly define nodules.

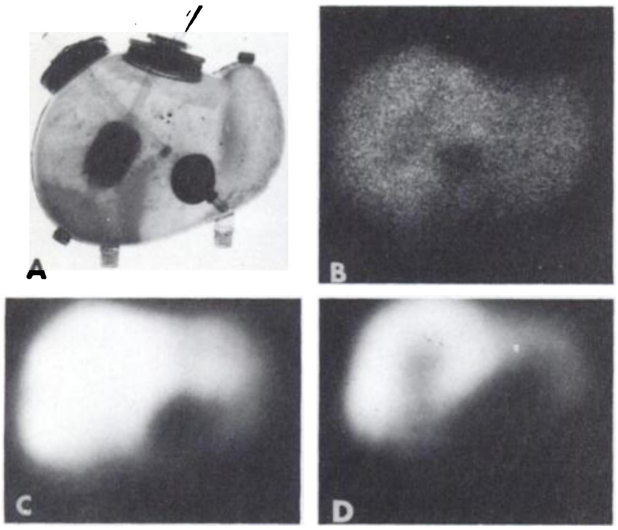

FIG. 10. Liver phantom. (A) Two defects are shown. Left lobe is thinned posteriorly to 50% of thickness of right lobe. (B) Scintillation camera (Searle Radiographics HP) image; ^{99m}Tc; made with 140-keV high-resolution collimator; 200,000 counts. (C) Zone plate 120 mCi-min. Anterior reconstruction. Left lobe defect only is seen. (D) Zone-plate posterior "cut": right lobe defect is seen. Focus is behind bulk of left lobe giving, perhaps, impression of large defect.

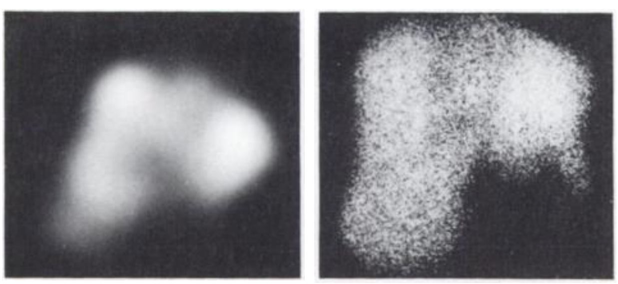

FIG. 11. ^{99m}Tc-sulfur colloid zone plate and scintillation camera pictures from patient with considerable hepatomegaly. Zone plate 120 mCi-min; scintillation camera as in Fig. 10. Two images correspond quite well.

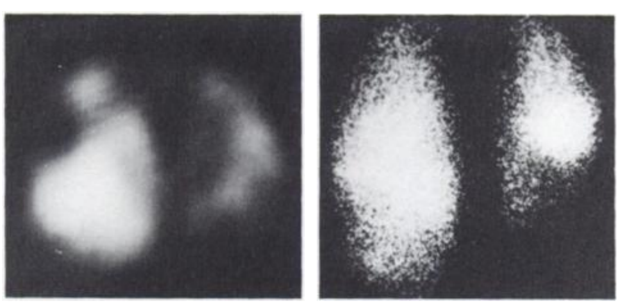

FIG. 12. Lung images in patient with chronic obstructive lung disease. ^{99m}Tc-MAA. Scintillation scan: anterior view, 200,000 counts; diverging 140-keV collimator. Zone-plate image made at 150 mCi-min. Right base was cut off but uneven perfusion is particularly evident in zone-plate image.

tential for providing better diagnostic information from radionuclide imaging.

The rather remarkable independence from scatter of the zone-plate images, demonstrated in the phantom studies and the clinical material, reflects at least three phenomena: (A) the system enhances contrast because the brightness of the light in the reconstruction is proportional to the square of the gamma-ray activity; (B) random scatter in the zone plate produces a uniform film fog that is ignored by the system; and (C) most importantly, the system records so much information that the images are usually not quantum limited as are those of conventional radioisotope imagers. The square law characteristic, however, can also at times be a disadvantage. For example, in Fig. 13 the normal spine is hardly visualized because of its lower uptake.

Tomography is particularly sharp (short depth of field) with this system. By virtue of this sharp tomography, the images of the thyroid demonstrate nodules that can only be inferred from the conventional scan image. Therefore, useful information is derived from the improved anatomic definition in these relatively thin organs.

With thicker objects, artifacts related to out-of-focus information appear and can be confusing. The reconstruction does not uniformly disperse the out-of-focus information. The resulting pattern of out-of-focus planes superimposed on the pattern in focus is occasionally confusing. In a thick object, the amount of out-of-focus data may be considerably greater than that arising in the plane in focus, thus degrading the image quality. Such artifacts have not invalidated interpretation and can be recognized when examining the reconstructions on a TV monitor by gradually and continuously varying the plane in focus.

In addition to artifacts caused by the out-of-focus volume of the object, image quality may also be degraded by having inadequate image information within the plane of focus (*7,8*). This degradation may be characterized by a signal-to-noise ratio (SNR) that is determined, in general, both by statistical fluctuations in the number of detected gamma-ray quanta and by film grain noise. For small objects, the film grain noise associated with the fog level of the film dominates. This noise is more or less signal-independent and the SNR increases linearly with exposure time. As the object size increases, the number of quanta required to give a certain quantum noise level in the image also increases (*8*). For very large objects (more than about 1,000–2,000 resolution elements) quantum noise will dominate and the SNR will increase as the square root of the exposure time. However, this limit will seldom be reached in clinical practice as long as x-ray film is used as the detector. Therefore, for a fixed total activity in the object, the required exposure time will usually increase linearly with object area just as in conventional imaging techniques. Stated differently,

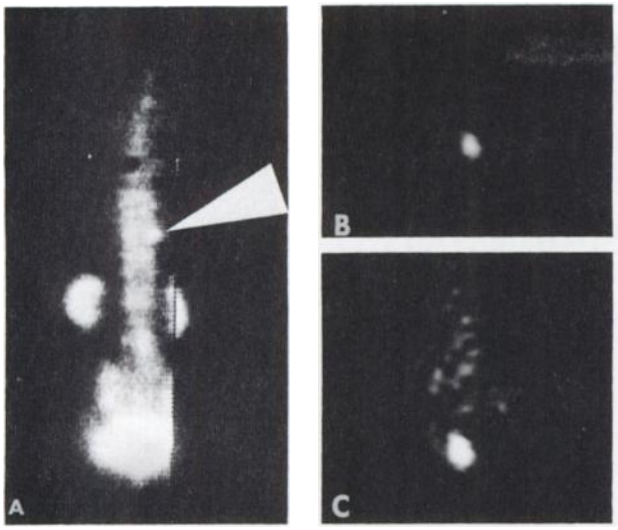

FIG. 13. Vertebral metastasis. ^{99m}Tc-polyphosphate. Rectilinear scan (A), zone-plate image (B), and overexposed zone-plate image (C). Metastasis so dominates zone-plate series that even overexposed copy gives little detail of normal bone. Kidneys, which are equally bright, were not in field of view of zone-plate imager.

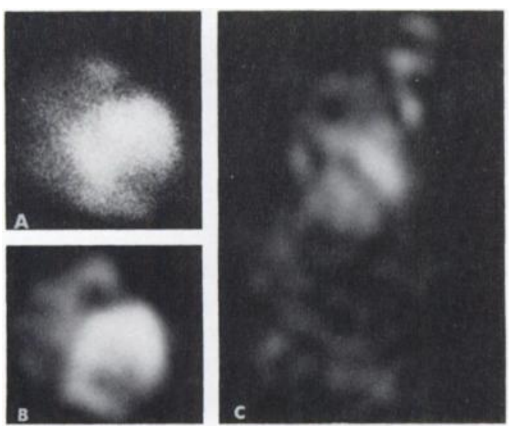

FIG. 14. Images of dog heart. Anger camera picture (A) and zone-plate camera reconstruction (B) were taken with excised heart. In vivo zone-plate picture (C) shows heart blurred by motion. Parts of liver and implanted cannula are also seen.

a certain minimum amount of information must be collected from each resolvable element in the object, independent of the other elements. Thus, with large objects, it may be necessary to reduce the resolution in order to get an adequate SNR in a reasonable time.

To make this discussion more quantitative, an acceptable image of a clinical thyroid using ^{99m}Tc or ^{123}I can be obtained with a dose-exposure product of 10 mCi-min whereas a very good image requires 20 mCi-min. (The dose here refers to activity in the organ.) These figures assume the use of commercial intensifying screens and a system resolution of about 5 mm. An improvement of a factor of 2–3 should be achievable by using thicker, noncommercial screens. For larger organs, such as the lung and liver, it was essential to reduce the resolution to about 1 cm, and even then the required dose-exposure product was about 120–150 mCi-min. For example, with an administered dose of 10 mCi of Tc-sulfur colloid for the liver and 80–90% uptake, an exposure time of about 12 min was required.

Note that the sensitivities quoted above refer only to medium-energy isotopes such as ^{123}I or ^{99m}Tc. As the energy is increased, the stopping power of the screen and hence the sensitivity degrades rapidly; the system is essentially useless for ^{131}I. By the same token, the performance improves at lower energy. For example, excellent images of the thyroid phantom filled with 1.0 mCi of ^{169}Yb have been obtained with an exposure of only 2 min. In this case, most of the exposure comes from the low-energy (50–65 keV) lines of the isotope.

These first clinical trials with an experimental zone-plate camera demonstrate a capability of increasing the anatomic definition and clinical information of some radionuclide images. The advantages of portability and independence from electronic difficulties are also attractive. The major disadvantage is the relative insensitivity of the camera compared with an Anger camera. Much work remains to determine the role of this device in the practice of nuclear medicine.

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