D. A COMPARISON OF THE LIXISCOPE WITH OTHER X-RAY IMAGING SYSTEMS

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The purpose of this paper is to review some basic imaging matters that are vitally important in determining the clinical potential of the Lixiscope.

1. Nature of Objects Examined

The objects so far examined with the Lixiscope share one or all of the following characteristics:

(a) high contrast,

(b) small thickness, and

(c) small area.

It is the possession of these attributes that has made it possible (and so convenient) to examine them with the Lixiscope in its present form, that is to say, with a screen of small area coupled to a low-energy nuclide source of modest activity.

Though objects simultaneously having all three properties do occasionally turn up in normal radiological practice, it is very much more common to meet subjects having only two or one or even none of these characteristics. Therefore, each of the above properties should be looked at to see how the Lixiscope and its radiation source must be modified to deal with more typical subjects. It is easiest to handle (a) and (b) together, since the contrast and thickness taken in combination largely determine the kind of radiation source that must be used.

2. Contrast and Thickness

In the human body substances such as bone, muscle, fat and air must be dealt with. Some of them (muscle and fat) have about the same density in g/cm^3, some of them (air, muscle and fat) have about the same atomic number and all of them have about the same number of electrons per gram (see Table 1).

Unfortunately, only if the tissues differ appreciably in at least one property—as bone and muscle do in atomic number or as air and bone do in g/cm^3—is separation of their images on the receptor possible. Even then, differences do not show up well, that is to say the contrast is poor, unless the photon energy is low. To get optimum radiation contrast, then, one needs to use the *lowest* practicable photon energy.

The use of low photon energies to accentuate contrast unfortunately carries a heavy and often unacceptable dose penalty. This is because the penetration of low-energy X-rays, though satisfactorily different in different tissues, is small in all of them, and a great deal of radiation must therefore impinge on the entrance surface of the patient if one is to get enough at the exit surface to actuate the radiation receptor (film, fluorescent screen, intensifier, etc.). From the point of view of reducing dose, the *highest* possible photon energy should be used, whereas contrast calls for the reverse. So in practice, some sort of compromise must be struck.

Table 1

	ρ	$\bar{Z}$	e/gram
air	1.29×10^{-3}	7.64	3.01×10^{23}
bone	1.85	13.8	3.00×10^{23}
muscle	1.00	7.42	3.36×10^{23}
fat	0.91	5.92	3.48×10^{23}

In view of the many sites at which radiographs are required and the tremendous variability among individual patients, it is difficult to make anything but the crudest generalization about the optimum operating point. For the sole purpose of discussing the Lixiscope, we may assume that a suitable energy is somewhere in the region of 35 to 60 keV; this corresponds with tube voltages of roughly 70 to 120 kV when X-rays are used.*

3. Source Energy

If the Lixiscope is to be operated with a radionuclide source it is first necessary to find a nuclide whose principal emission is somewhere in the above energy region. A quick search reveals some ten or twelve potential sources, but closer examination shows that several of the candidates selected on an energy basis are unsuitable on other grounds. Some of them, for example, emit gamma rays and/or characteristic X-rays that lie at undesirable energies, in addition to the principal radiation that would make them useful for Lixiscope work. In some, such as Tm 170, there is an intense Bremsstrahlung component generated by accompanying beta emission; some have inadequate half-life; some, such as gaseous Xe 133, are in an unsuitable physical form, and so forth. Considerations such as these further limit the practical possibilities.

**The photon spectrum emitted by a tube working at e.g. 100 kV, contains very few photons with an energy of 100 keV. These are accompanied by a vast number with considerably lower energies, so that the average energy is only ½, or less, of the maximum possible value.*

4. Geometry

To the difficulties of finding sources with suitable energy and half-life must be added even more severe *restraints arising from the geometrical requirements* of image formation. The most notable of these is that the source of radiation, for reasons to be explained in a moment, should be as far from the radiation receptor as possible, while the object to be radiographed should be as close as possible to it; that is to say, the source-receptor distance should be much larger than the object-receptor distance. In the case of thin objects such as human jaws and small animals, the requirement of relatively large source-receptor distance can be met easily enough; but in the more usual case of the human torso, it may be necessary to station the source at a meter or so from the receptor. This requires that very large source strengths be available if an image is to be formed in a reasonable time.

The reasons why the source-receptor/patient-*receptor distance ratio should be large are to reduce* image unsharpness, to reduce magnification and distortion, and to increase the effective penetration of the radiation through the patient:

(a) *Unsharpness:* To produce a perfectly sharp image by shadow-casting (and radiography must rely on such a process because X-rays are not usefully refracted or reflected, and so cannot use image-forming elements of the optical type) it is necessary to use a point source of radiation.

A practical source, whether it is the anode of an X-ray machine or a radionuclide, unfortunately has a finite size. Now each point on the surface of a finite source may be considered to cast its own image of the object, and the final image seen on the receptor is a composite of all the images cast by the multitude of points making up the finite source. In Figure 1 (a), for example, the left margin of the source images one edge of an object at A, whereas the right side of the source images the same edge at a point B slightly displaced from the first (Figure 1 (b)). The existence of this partially-illuminated or penumbral region between A and B means that the edge of the object is undesirably blurred (Figure 1 (c)).

Figure 2 shows that the penumbral region (and the blurring) gets smaller as the source moves away from the receptor, assuming that the object-receptor distance is unaltered. For a given source size, then, it is always advantageous to back the source off from the surface of the patient until, when the source is far enough away, its dimensions as far as penumbra formation is concerned are effectively zero and the ideal point-source condition is realized.

(b) *Magnification and Distortion:* Because, as just seen, the radiographic image is really a shadow, the image is always bigger than the object, and the receptor must therefore be larger than the anatomical area that one wants to observe. This severely limits the usefulness of a small-area detector such as the present Lixiscope. The only way to overcome this limitation (unless sequential scanning is used, as described in Section 5) is to make the Lixiscope screen at least as large as the anatomy.*

**but see Section 6*

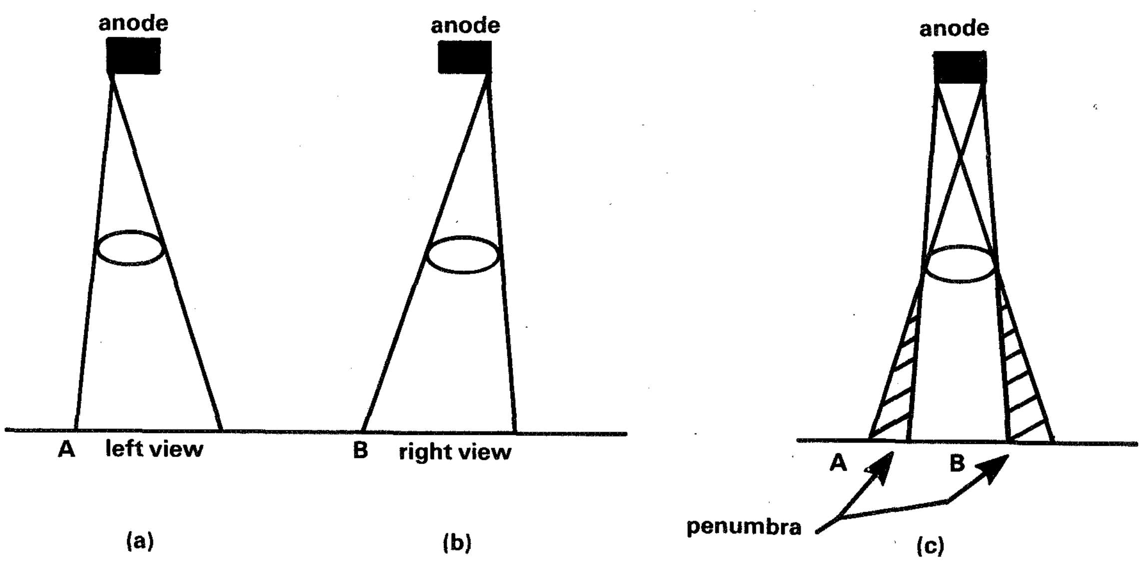

Figure 1.

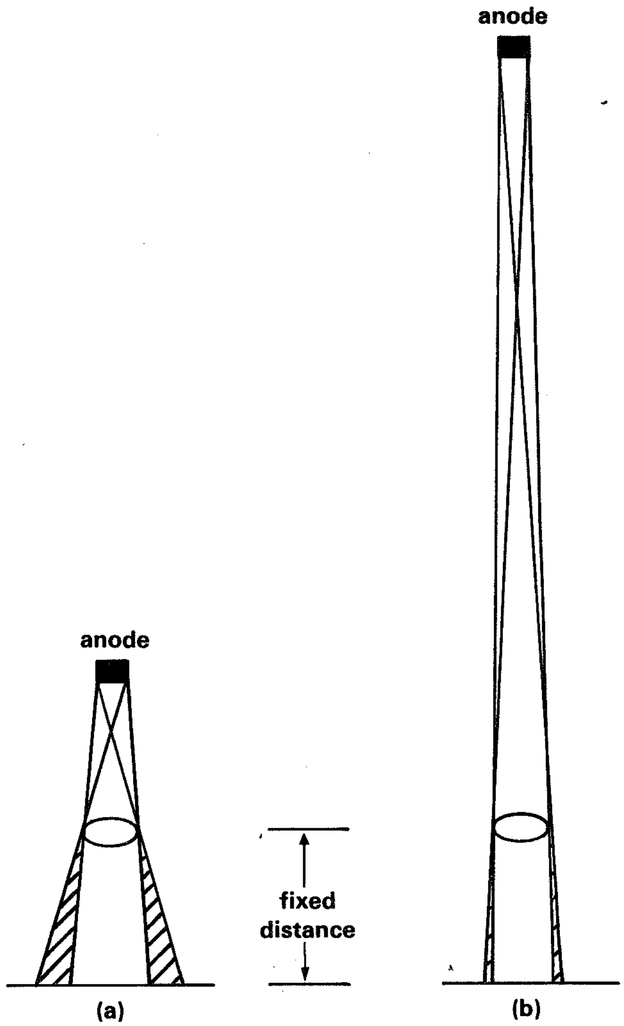

Figure 2

This requirement is least crippling when the source-receptor/patient-receptor distance ratio is maximized—a step we also wish to take for reasons given in the discussion of unsharpness—because the magnification diminishes as the distance ratio increases, falling to unity when the ratio is infinite (Figure 3).

The presence of magnification introduces **another distressing complication; the patient is never as thin as the object shown in Figures 1(a) and (b), so the parts of him closest to the source are magnified more than the parts closest to the receptor (Figure 4(a)). This differential magnification leads to a potentially confusing distortion of the image. Again, however, this effect will be reduced by backing the source away from the patient's skin (Figure 4(b)).**

(c) *Effective Penetration:* A third reason for using relatively big source-receptor distances, even though they demand large source activities, is that the effective penetration of the photons is thereby increased. This comes about because the relative importance of one of the two photon attenuation processes is diminished at large distances.

The attenuation mechanisms at work in any radiographic procedure are (a) photon removal through photoelectric absorption or through scattering encounters that deflect photons out of the useful beam and (b) inverse-square fall-off or geometrical attenuation. The latter arises because the source is a point that emits its photons in straight lines equally in all directions; a given batch of photons therefore has to spread itself over an ever-increasing area as the point of observation recedes from the source. The net result is that the photon flux, expressed in photons/cm^2, depends inversely on the square of the distance from the source; this (b)-type inverse-square dilution occurs simultaneously with any (a)-type absorption or scattering processes and its effect is always to reduce the effective photon penetration below the value that would be observed if only (a)-type processes occurred.

It turns out that the undesirable effects of geometrical dilution are reduced (as were unsharpness, magnification and distortion) by using the largest possible value of the source/object distance ratio. In Figure 5(a), for example, the inverse-square law dictates that not more than 25 units of radiation can emerge from the underside of the patient for every hundred units put in at the top *even if there were no absorption at all.* In Figure 5(b) on the other hand, where the source-receptor distance has been increased, keeping the patient-receptor distance constant, the inverse-square reduction is less severe and the maximum possible emergent amount (assuming (b)-type attenuation only) is 83 units for every 100 units entering at the top.

The accompanying (a)-type processes will of course reduce the emergent intensities in both Figure 5(a) and Figure 5(b) by an additional large factor that is however roughly the same in both cases. This means that the emerging intensities will still be in the approximate *ratio* calculated using the inverse-square law alone, even though the absolute value of each intensity is greatly reduced by (a)-type processes (in Figure 5, the (a)-type reduction is taken as 0.1). If matters are adjusted so that the *exit* (rather than the entrance) intensity is the same in both cases and is just adequate for Lixiscope viewing, the examination can be made with far less entrance dose to the patient using the set-up of Figure 5(b) than using the arrangement of Figure 5(a).

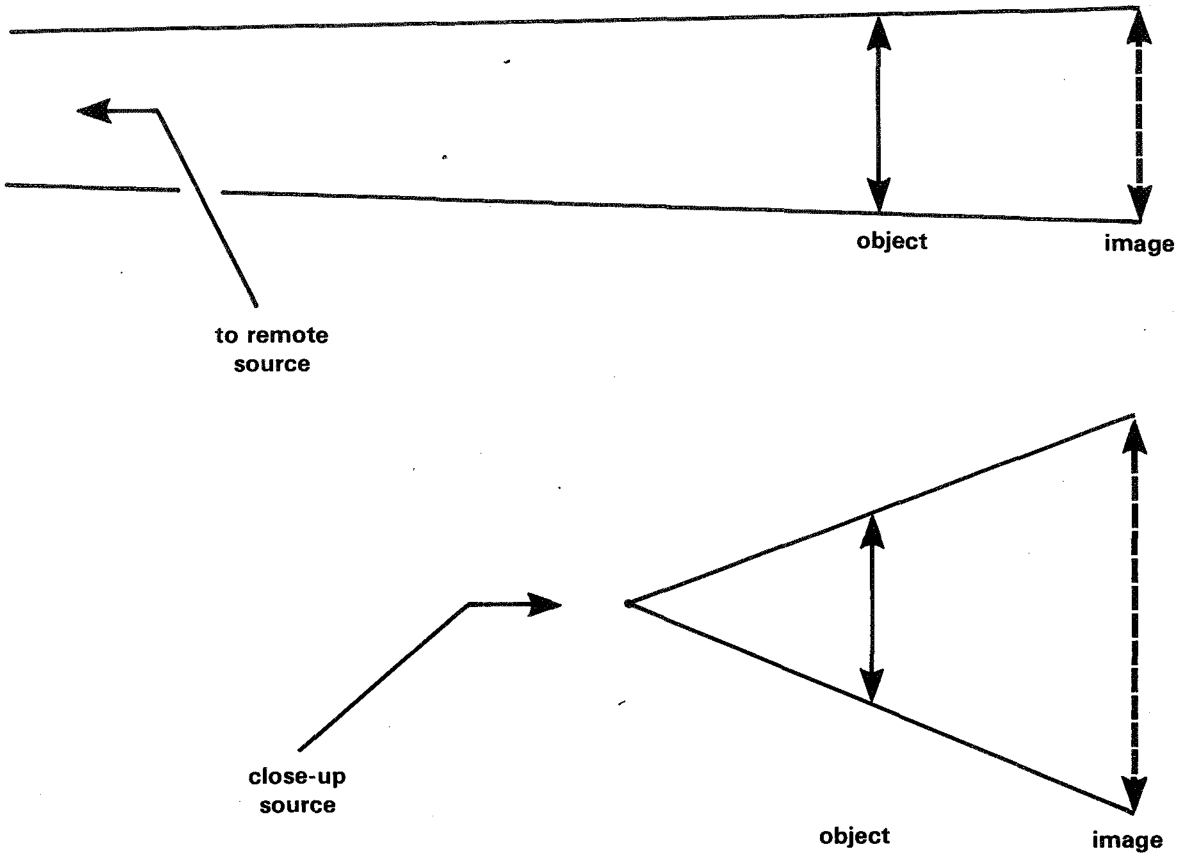

Figure 3. Magnification is Less at Large Source-Receptor Distances (Top Figure) Than at Small Distances (Lower Figure). At Infinite Distance There is No Magnification

5. Source Strengths

For all these reasons, it is highly desirable to examine typical subjects at very much greater source-receptor distances than it is possible or necessary to use in certain kinds of dental or small-animal study. Very rough calculations, based on the figures Drs. Yin and Seltzer have given for the I-125 sources that they have found usable at short distances, indicate that source activities of some 2 or 3 Ci (curies) will be necessary at working distances of 100 cm or so.

Quite apart from the initial and frequent renewal expenses, the considerable hazard, and the difficulty of obtaining possession licenses for activities of this order, another problem is encountered with most available nuclide sources. The volume of a source, other things being equal, depends on the product of the mass number and the half-life, divided by the physical density of the source material. It also depends on the decay scheme (which essentially tells the number of desired photons produced in one disintegration) and on whether or not the source can be made carrier-free, that is, on whether all of it is radioactive or whether it includes inactive material that adds unwanted volume without contributing to the activity. When these additional considerations are brought to bear, it emerges that only one or two commonly-available sources have any real hope of filling the bill; they are I-125 and Am-241. Unfortunately, the energy of I-125 is rather too low for objects of appreciable thickness. Am-241, with its higher energy, at first sight looks quite promising but the theoretical maximum specific activity is about 3.3 curies per gram. This means that the diameter of a carrier-free source with an activity of 2 or 3 curies is a few mm, which is very much greater than the focal-spot size in a typical X-ray tube. No doubt there are other nuclides that could be used* but the point is that the choice is very limited.

For this reason, work on nuclide-Lixiscope combinations should be somewhat de-emphasized, except in applications where portability is the prime requirement and/or the objects happen to be suitable for short-distance low-activity work; the notion should be discarded that nuclide sources must

See "Some Remarks on X-ray Source Characteristics and on Detection Efficiencies of Prototype* ***Lixiscopes,**" Dr. Stephen M. Seltzer, Center for Radiation Research, National Bureau of Standards (p. 26).*

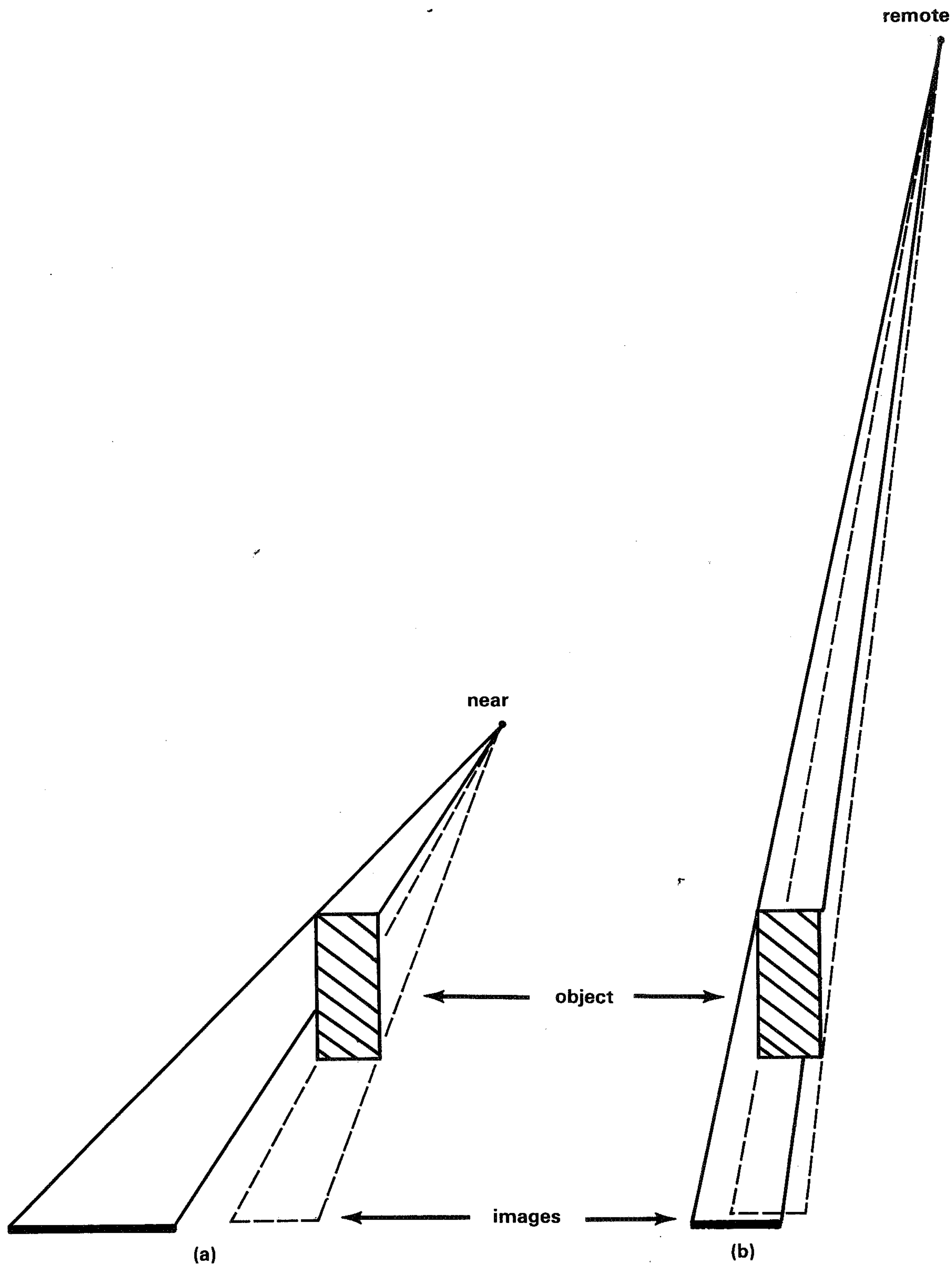

Figure 4. Image Distortion is Less at Large (4(b)) Than at Small Source-Receptor Distances (4(a)).

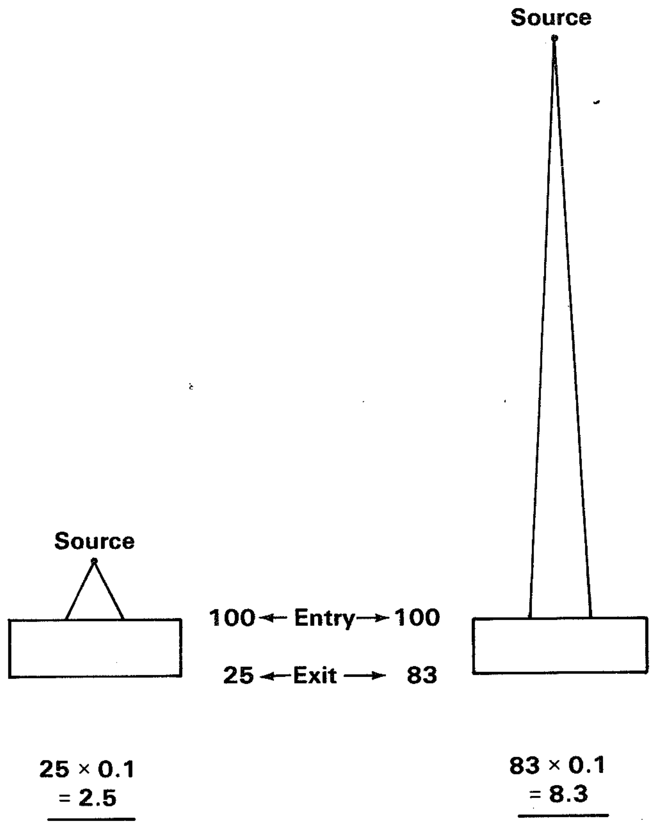

Figure 5

forever be an essential part of the Lixiscope just because they played an important part in its original development. Once free of the nuclide emphasis, the Lixiscope may evolve as a new and very advantageous version of just one link (the standard image intensifier) in the imaging chain and not as a replacement for all links simultaneously. If this is done and attention is given to modifying the "back end" of the present instrument so as to give it some of the desirable characteristics mentioned below, a very rapid development should result.

The key is to switch from gamma-ray to X-ray sources. With such sources, the vastly greater photon output is adequate for work at the large distances needed for good image quality and higher effective penetration. The effective photon energy can be readily changed to suit the object under investigation, the source diameter can be made small enough for good detail, and the constant hazard encountered with nuclide sources can be eliminated at will simply by switching the machine off. Last but by no means least, licensing becomes a very much simpler process. Use of an X-ray source reduces portability, but the problem is not insoluble since portable generating equipment of field-emission and other types is commercially available.

If one then ceases to worry about the source and concentrates on receptor development, the first problem that needs to be tackled is that of image area. A patient's skull, for example, could show an anomaly that may not be detected with a small-screen receptor unless the screen is properly positioned at the first try or unless many exposures are made, thereby building up a large image from a mosaic of smaller ones.

With existing Lixiscopes, a scanner to make the required mosaic could be built, as shown in Figure 6(a). In this figure, a large beam of X-rays covers the total anatomy that is potentially involved. At the exit side of the patient, a lead screen is placed to shield the observer from the instantaneously unused part of the beam; the Lixiscope exit face must also be screened with lead glass, of course.

With this apparatus, an arbitrarily large area could be examined, given enough time, but examinations involving dynamic processes over such a large area are clearly ruled out; besides, the dose is increased over the minimum necessary with a large-screen device in the same ratio as the total observing area bears to the area of the Lixiscope. This dose difficulty can be eliminated by placing the patient between two shields and linking them with the Lixiscope and with the radiation source so that they all move as one unit during the scan (Figure 6(b)). However, the time-penalty still remains.*

6. Gamma Camera Applications

One of the few fields where the small area of the present Lixiscope, though disadvantageous, is not entirely crippling, is in the examination or self-luminous gamma-sources. Examples are implanted radioactive needles (cesium 137, radium, iridium 192, gold 198, tantalum, etc.) and ingested or injected sources such as iodine 131 or technetium 99^m.

In such cases, one can make use of the pinhole camera principle, whereby the source "projects" an image of itself onto the Lixiscope through a very small hole in a plate otherwise opaque to the emitted radiation (Figure 7). This scheme is widely used in certain of the gamma cameras so familiar in nuclear medicine departments, though the receptor in those cases works on a somewhat different principle. By suitably choosing the distances d_1 and d_2, it is possible to produce an image that is diminished (or alternatively magnified) to any extent desired, and can easily be made small enough to fit on the screen of the present Lixiscope.

This approach was tried at Duke, with the help of Dr. J. K. Goodrich** by mounting a tungsten shield containing a biconical hole of 1 mm diameter in front

An interesting point about the dual-shield scanner is that the volume of tissue instantaneously irradiated is quite small and the disturbing effects of scattered radiation at the receptor are greatly reduced, possibly eliminating the need for the anti-scatter grids normally used in radiography.

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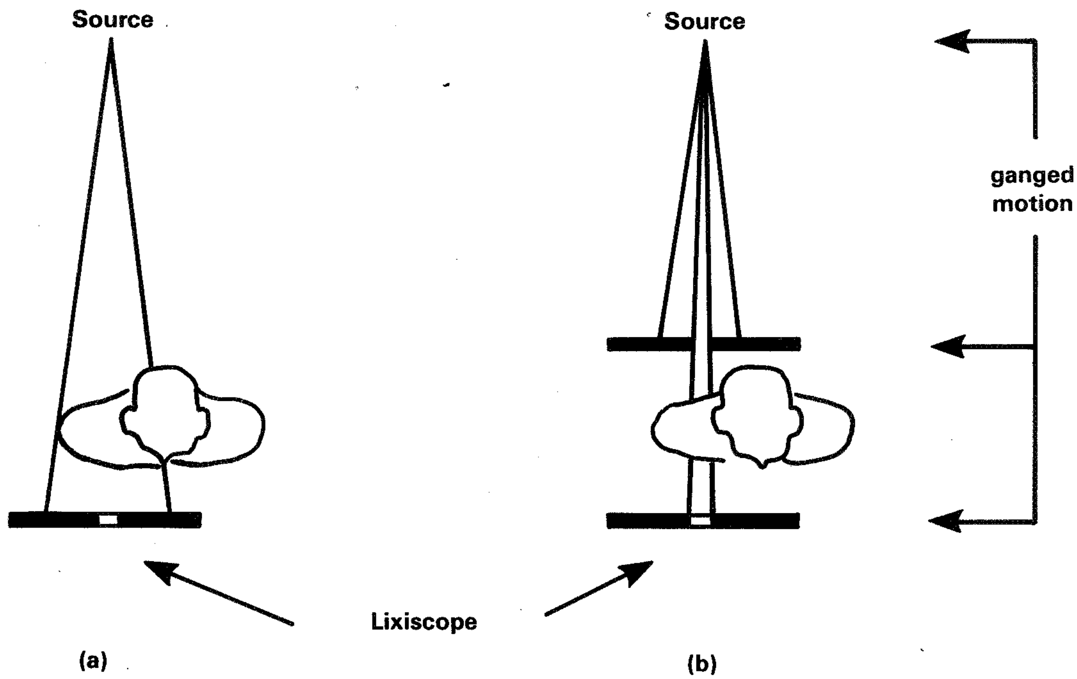

Figure 6

of the Lixiscope and photographing the output screen with an oscilloscope camera. (See Figure 8.) With this apparatus, which had provision for varying the pinhole-Lixiscope distance so as to change the magnification continuously, we were able to produce images of a 100 mCi Am 241 disc source. With approximately the same Te 99^m activity, we could photograph liquid-source containers at reasonable resolution in geometries that would be conveniently usable in thyroid function studies, but the observation times were unacceptably long. With Ir 192 in the form of implantable "seeds", the images were of much poorer quality, most probably because pinhole edge-penetration effects are appreciable at this higher energy (~0.4 MeV). With radium needles (~1 MeV average energy), no more than a reasonable indication was gained of the presence and layout of sources, and the pinhole design will have to be modified—and the screen sensitivity greatly increased—if the Lixiscope approach is to have any great utility in this energy region. This energy-limitation is not a special characteristic of the Lixiscope, however, and the drawback is shared with other gamma cameras; so also is the flaw that the Lixiscope sees only the sources, whether they be concentrated or diffuse, and not the inactive ("cold") anatomy in which they are situated.

These experiments demonstrate the great potential of the Lixiscope as a compact and inexpensive gamma camera, usable in both industrial and medical applications. For routine medical use, however, improvements in the present model are necessary. One is to increase the area, since too much minification is at present needed, and another is the substitution of a much more efficient detector for the existing input screen. A thin crystal of sodium iodide, for example, would greatly enhance the sensitivity. This aspect of Lixiscope development should be pursued with vigor, as the possibility of a hand-held gamma camera is a very attractive one.

It is even conceivable that two such cameras, viewing a nuclide-filled organ or region, would provide a degree of on-line stereoscopic vision that might be extremely useful in areas such as nuclear cardiology. In this connection, it is worth remarking that the inverting stage which seems to be responsible for the lower gain of some existing Lixiscopes, should be retained in gamma-camera applications where it would rectify the automatic image inversion produced by operation of the pinhole-camera principle (see Figure 7); visual observation without the additional inverting stage would be quite confusing.

7. Future Developments

A pressing problem that will remain when large-area Lixiscopes become available is that there is no contrast amplification, because of the nature of the fluorescence mechanism; this serious drawback is shared with existing image intensifiers. Unless some contrast gain can be introduced (possibly by photographic or electronic means), the utility of the

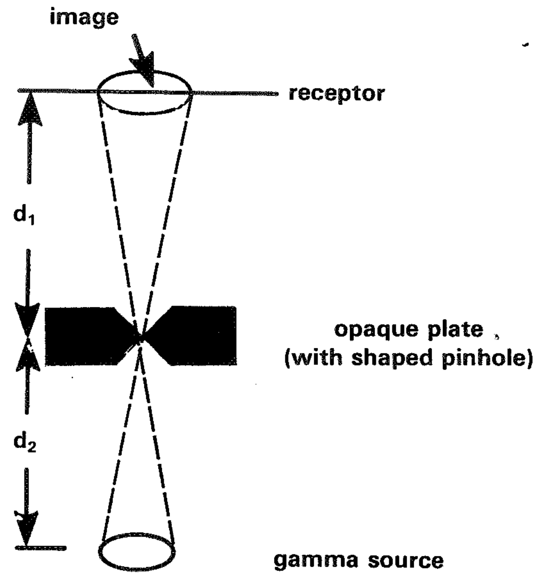

Figure 7

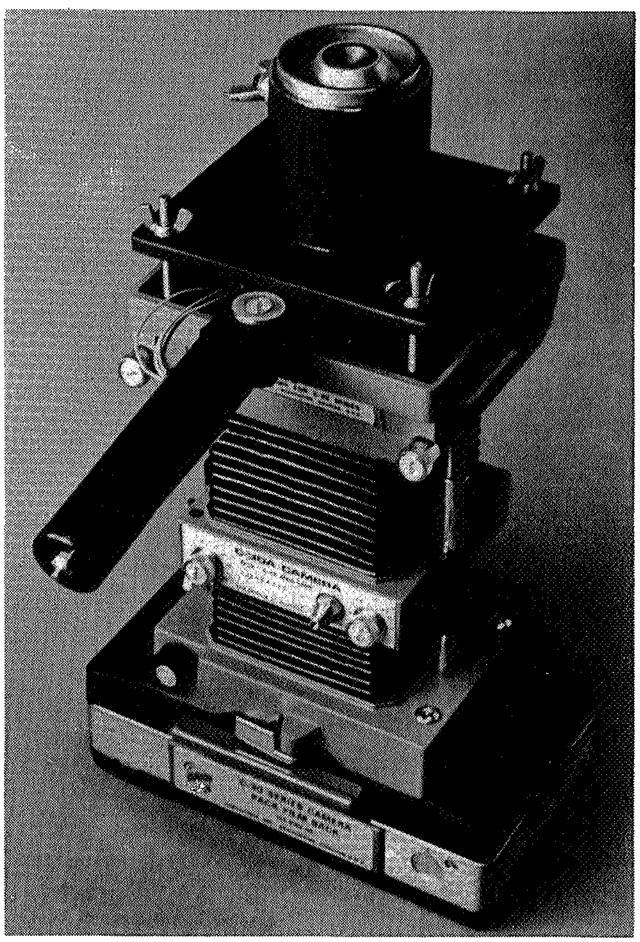

Figure 8

device will suffer in examination of low-contrast objects. However, it appears that the multipliers in the microchannel plate can be addressed individually, at least in principle. If this is so, then contrast manipulation (including edge enhancement as in the present Xeroradiography system) becomes possible and would repay study.

A further interesting possibility arises. If, when individual addressing becomes possible, some kind of energy discrimination were also introduced, then one would have a large-area detector with both spatial and energy resolution. This could be applied to the ever-present radiological problem of scatter suppression if a source of monoenergetic radiation were also available, since the scattered radiation that degrades the image could then be discriminated against on the basis of its reduced energy. For reasons already discussed, gamma-ray sources are unsuitable (although they are essentially monoenergetic), but Duke has gone some way in developing a single-energy X-ray source in the form of a rhodium anode tube, and we are now working on other fluorescent anodes from which intense monoenergetic radiations of different energies are emitted. A combination of these tubes with an energy-selective Lixiscope would be a powerful tool in radiography, permitting scatter suppression with essentially no loss of primary image-bearing radiation, thereby decreasing the required patient dose. In the nuclear medicine field, energy discrimination would not only reduce background (as in the standard gamma camera) but would permit simultaneous observation of more than one nuclide, possibly with digital manipulation of several images simultaneously.

8. Conclusions

The limited opportunity Duke had to work with the Lixiscope has led to the following conclusions:

1. Operation of the device with a nuclide source, while profitable in certain limited applications, is unlikely to be useful in the more standard radiological procedures. Greater effort should therefore be devoted to combining the Lixiscope with an X-ray source to provide a convenient, inexpensive and portable alternative to conventional image intensification systems.
2. High priority should be given to the development of much larger viewing screens.
3. The Lixiscope has great potential in nuclear medicine as a complement to the gamma camera.

"Complement" is indeed the key word. It is quite unlikely that the Lixiscope will ever completely supplant more conventional radiographic and fluoroscopic equipment, but it will undoubtedly complement these techniques in certain situations, where its use will give greater convenience in bulk and portability and, very probably, will save expense; this is particularly true and almost immediately realizable in the field of nuclear medicine and will become apparent in radiographic and fluoroscopic applications as large-area screens and miniaturized X-ray supplies are developed.