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Optical Processing of Radionuclide Images

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ABSTRACT

The quality of radionuclide images is limited by the spatial resolution of the collimated radiation detector, noise due to random fluctuations in the signal level, and line structure due to the rectilinear scanning motion of the detector. Within the limits of a useful signal-to-noise ratio, such images can be altered in various ways by optical spatial filtering techniques. Sharpening is accomplished by removing the low spatial frequency components from the image, which (relatively) enhances the high frequency components. Smoothing of recorded noise is accomplished by removing the high frequency components that lie above the detector bandpass. Line structure is removed by a special filter that blocks the periodic pattern which characterizes the scan raster. In this pilot study, an inexpensive HeNe laser and simple lenses comprise the optical system.

INTRODUCTION

In recent years, radionuclides have been used in a variety of medical diagnostic tests (1,2). For example, brain lesions may be detected if they perturb the normal distribution of radioactive material administered to the patient. In the interest of a low radiation dosage to the patient, only a small quantity of radioactivity can be used in such tests. As a consequence, the need

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for high sensitivity places a severe limit on the spatial resolution of radiation detectors designed for radioisotope imaging devices. At best, the resulting images exhibit noticeable imperfections in the form of noise (resulting from random fluctuation in the number of detected γ -rays recorded per unit area), and distortion (mostly smoothing, due to imperfect spatial resolution), scanning artifacts (line structure, scalloping, etc.).

To increase the perceptibility of low contrast, unsharp, structures that are relevant to an accurate diagnosis, a variety of analog (3-5) and digital (6-10) techniques of image recording and manipulation have been employed with some success. Here we present the results of our preliminary studies of optical spatial filtering techniques for image manipulation.

ESSENTIAL ELEMENTS OF THE THEORY

The basic physical theory underlying optical spatial filtering extends at least as far back as Abbe's theory of the microscope (11), but has been developed and applied extensively in recent years, as intense sources of coherent light have become available. Briefly, this development has made use of the concepts of communication theory in the analysis of optical systems, objects and images being described in terms of their spatial frequency components, and optical systems in terms of their spatial frequency response. The theory has been presented in elegant mathematical form in numerous publications (12-17). Here, we shall only recall a familiar observation concerning diffraction gratings which suggests the plausibility of the theory, and state the general theorem on which the spatial filtering procedure is based.

It is well known that a beam of monochromatic coherent light falling on a plane periodic structure, such as the square-wave transmission grating, shown in Figure 1, is diffracted at angles $\pm \theta_m$ such that

$$\sin \theta_m = \frac{m\lambda}{d}, \quad (1)$$

where $m = 1, 2, 3, \dots$ is the diffraction order, λ is the wave length of the light, and d is the grating spacing. As a result, the distribution of light in the back focal plane of a lens having focal length f is a Fraunhofer diffraction pattern with peaks at distances y'_m from the axis, given by

$$y'_m = \pm f \tan \theta_m \cong \pm f \sin \theta_m = \pm \frac{fm\lambda}{d} \quad (2)$$

for small angles θ_m .

What is crucial to the spatial filtering procedure is the fact that the Fraunhofer diffraction pattern is proportional to the Fourier spectrum, or spatial frequency spectrum, of the diffraction grating. In this particular case, the one-dimensional square-wave transmission grating has a discrete Fourier spectrum that consists of an average, or DC component, a fundamental AC component $\nu = 1/d$, and integral multiples $\nu_m = m\nu$ of this fundamental frequency. That is, the sinusoidal plane wave frequency components comprising the diffraction grating give rise to a light amplitude distribution in the back focal plane, each component ν_m giving rise to the two light spots at

$$y'_m \cong \pm f\lambda\nu_m \quad (3)$$

This observation lends plausibility to two more general statements. First, the frequency spectrum of any one-dimensional transparency in the object plane (replacing the square-wave grating) appears in the back focal plane (also called the frequency plane) with the sinusoidal plane wave component having frequency ν in the object giving rise to light at two small regions with centers at

$$y' \cong \pm f\lambda\nu \quad (4)$$

Second, the two-dimensional spatial frequency spectrum of any two-dimensional transparency in the object plane appears in the frequency plane. This generalization covers the case of photoscans produced by radionuclide imaging systems, and is therefore the theorem underlying this study. The essential mathematical relations are summarized in the Appendix.

Since the spatial frequency components of any such object transparency are separated spatially in the frequency plane, we can place a filter there, which is more nearly opaque* for those components we wish to attenuate than for those we wish to accentuate. The filtered image is formed from those components allowed to pass the frequency plane.

A great variety of filters can be imagined. Some of the simplest, sharp-cutoff types are shown in Figure 3. In each case the outer circle with radius R_c corresponds to the maximum aperture in the frequency plane, and this corresponds to a certain high frequency cutoff point, given by $\nu_{\max} = R_c/f\lambda$. Thus, the optical system is always band limited, and can form potentially perfect images of only those objects with spectra lying within this band.

*In addition, to amplitude filters described here, phase filters may be used for image manipulation (15,17).

Within this aperture, all lower frequency components appear, with zero frequency, or the DC component, on the axis. A low-pass filter consists simply of an aperture smaller than R_c , while a high-pass filter is opaque on and near the axis. Combining these types, a band pass filter can be achieved. Finally, a line-stop filter for frequency ν , can be approximated by an opaque ring with radius $r = f\lambda\nu$ placed in the frequency plane.

PROCEDURE AND RESULTS

The system used in these studies is shown in Figure 2. This configuration has been described in detail by Cutrona et al. (14). An Optics Technology Model 170 HeNe laser was used as a source of monochromatic coherent light with wave length $\lambda = 6328\text{\AA}$. A double concave lens L_1 , with a short focal length, was used to expand the laser beam to about 1.5 cm diameter. All object transparencies were copied from original photoscans using Polaroid P/N film, and reduced to a maximum diameter of ~ 1 cm. This is necessary if the laser beam is to cover the entire object to be filtered. In addition, this reduction increases the effective frequency ν in the object and magnifies displacements y' in the frequency plane in accordance with equation 4. The lenses L_1 , L_2 , and L_3 are identical simple plano-convex uncoated lenses with a focal length of 483 mm. L_2 collimates the laser beam onto the object transparency to be filtered; L_3 focusses the diffracted beam onto the frequency plane where the object spectrum appears; and L_4 reforms the filtered image on the image plane. A single-lens reflex camera was used to record the filtered images on Kodak Plus-X film.

Figure 4a shows the unfiltered image of a square wave sunburst pattern projected through the system. Figure 4b shows the effect of placing a low-pass filter (a hole about 0.7 mm in diameter in black construction paper) in the frequency plane. In this case, the low frequency sinusoidal components below $\nu = 0.72$ cycles per cm were passed by the filter while all components with higher frequency were eliminated. The sharp cutoff characteristic of this filter is very evident in Figure 4b.

The effect of this filter on a photoscan is shown in Figure 5. The unfiltered image of the head and neck regions of a total body scan appears on the left in Figure 5a. This image was made by recording a tiny dot on film for each detected γ -ray (18). The high frequency components of these dots were eliminated by the low-pass filter; this resulted in a smoothing effect which may be seen in the filtered image in Figure 5b. This technique can be used to remove details that

are regarded as too small to be diagnostically meaningful.

On the other hand, we would like to sharpen the somewhat larger details that might be meaningful. To accomplish this, a filter of the high-pass type, which attenuates low frequencies, was used.

For this purpose, a quartz fiber was drawn down to a diameter of 0.006" or 0.15 mm; a 90° bend was made about 0.5" from the tip, and the entire structure was blackened with a spray graphite film. When mounted on the optical axis in the frequency plane, this tip blocked the DC component and all low frequencies up to $\nu = 0.16$ cycles per cm.

Figure 6c shows the result of using this filter to sharpen a brain scan of marginal quality, which was originally produced in a scanning time of just 90 seconds (19). In this case the number of counts per unit area was quite small and the use of a large step width between scan lines resulted in a relatively poor image, which nevertheless shows a lesion. Filtering a scan of this type to enhance the high frequency components does sharpen the small structures, including the lesion; however, this process introduces the danger of enhancing small structures that are not statistically significant, and fragmenting integral structures, such as the tumor. This is the principal limitation of the technique.

A quite different type of filtering operation can be performed on such a brain scan, which results in the elimination of the line structure. For this purpose, the filter was made by placing in the object plane a uniform line pattern having the same spacing as the line structure in the brain scan. The filter, consisting of the frequency components of this periodic structure, is obtained by placing a piece of film in the frequency plane. (See Fig. 7). When this film is developed and put back in the frequency plane, it filters out the line structure. Figure 6d shows this effect; that is, the photoscan in Fig. 6b yields the image in 6d when the line structure is filtered out. Note that other structures are neither sharpened nor appreciably smoothed, while the line structure has been eliminated.

DISCUSSION

This study was undertaken to gain some familiarity with the effects of coherent optical spatial filtering techniques on radionuclide images. As such, the study reveals some of the image manipulations that are very easily achieved, and should not be interpreted as indicating the limitations of the technique.

Indeed, the apparatus and procedures could readily be improved in the following ways:

- 1) The technique is based on the assumption that the light source is spatially coherent. This condition could be achieved to a much higher degree by passing the laser beam directly through a tiny aperture with a diameter of 25μ to 50μ . In that case, a laser with a higher output power could be used to obtain a suitably short exposure time.
- 2) The lenses used were very inexpensive and of correspondingly limited quality. Better results could doubtless be obtained with better lenses.
- 3) The components of the system were not mounted on a vibration-free optical bench, which might also have afforded the improvements associated with proper alignment of the optical axis.
- 4) No special precautions were taken in copying the original photoscans on a reduced scale for filtering. In fact, the photographic technique should be regarded as marginal at every step in the procedure. If spatial filtering were to be used as a routine procedure, it would be desirable to eliminate the photographic reduction step by recording a minified image which could be filtered directly.
- 5) To reduce the effects of phase shifts that result from different optical path lengths through developed film, the object to be filtered and the filter itself should be immersed in "liquid gates" having optically flat surfaces and containing a liquid with an index of refraction matched to the film base (20). Such gates were not used.
- 6) The filters used were of the sharp amplitude cutoff type. Additional control of image manipulation could be achieved by utilizing continuous complex filters having both amplitude transmission and phase shift characteristics (15,21).
- 7) Ultimately, the desired filtering process might be performed by the recording device itself. The rationale for this approach is suggested by the following considerations.

The collimated scintillation detectors used in radionuclide imaging systems can be regarded as low-pass filters, with a cutoff frequency ν , (typically below 1 or 2 cycles per cm), which is determined by the shape (especially the width) of the detector point-spread function (22). Similarly, the recording devices used in these systems can also be described as low-pass filters with a cutoff frequency ν , that is determined by the shape (especially the width) of the mark or spot recorded for each detected γ -ray. For example, if very

tiny dots $[\delta(x,y)$ functions, in the limit] are recorded, then ν_R may be very high $[\nu_R \rightarrow \infty, \text{ in the limit of } \delta(x,y) \text{ functions}]$ and may easily exceed ν_D .

Since meaningful structures in the recorded image are band-limited by ν_D of the detector, any spectral component with $\nu > \nu_D$ appearing in the image is due to the recording device. It would be desirable to eliminate such components from the recorded image, since they contribute only to the noise power spectrum (23), and there is no reason to believe that their presence increases the perceptibility (24) of structures to which the detector may have responded.

To eliminate all noise above the detector band pass, the spot shape of the recording device should be designed so that $\nu_R \leq \nu_D$.

This condition could be achieved by a variety of recorded spots; e.g.:

- a) A spot with the same size and shape as the point spread function of the detector would result in a recording device with the same spatial frequency response as the detector; however, this recording device would degrade the image contrast at frequencies $\nu < \nu_D = \nu_R$ just as the detector does. (To prevent this degradation, while eliminating some of the high frequency noise, a bell-shaped spot that is smaller than the detector point spread function is used to record brain scans (19), such as the one shown in Figure 6b).
- b) A spot with the shape of $J_1(r)/r$ could provide flat frequency response over the detector band pass, and no response at higher frequencies; however, this function has negative lobes that may require a DC off-set if negative inputs to the recorder are not feasible.
- c) A spot with a shape that would provide a recorder frequency response that was the inverse of the detector frequency response would precisely compensate for the smoothing effects introduced by the detector, so that the overall response would be flat. The utilization of such an equalization filter (or apodizing filter (15)) is limited to the frequency band over which the signal-to-noise ratio is regarded as adequate.
- d) An "optimum" spot shape would in general depend on the choice of a criterion for optimization. For example, we may choose to minimize the rms deviation between object and image, where deviations may be both random (due to noise) and deterministic (due to distortion) (25).

Linfoot (26) has discussed alternative criteria, based on the correlation between object and image, and relative structural content.

- e) If the size and shape of structures relevant to a correct diagnosis were known, the spot shape might be designed to enhance these structures.
- f) If more were known about parameters affecting the perceptibility of structures in a complex field, these factors might be taken into account in designing the spot shape.

Until it is demonstrated that some particular manipulation of the image (or set of manipulations) increases the likelihood of a correct diagnosis, the safest procedure will probably be to record faithfully the detector output for non-destructive post-scan manipulation. Optical spatial filtering techniques appear to provide a simple means for carrying out these manipulations, so that their effects on diagnosis may be studied.

CONCLUSIONS

Coherent optical systems provide a very versatile technique for photo-scan image manipulation. In practice, the technique may have advantages over digital computer manipulation, so long as the diagnosis is based primarily on a visual examination of the image, rather than on quantitative data extracted from it.

Whether or not any such technique of image manipulation will significantly aid in diagnosis remains to be seen. If, however, it could be demonstrated that some particular manipulation was helpful, attention should probably be directed toward designing recording devices that would introduce this manipulation in the recorded image.

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APPENDIX

If the two-dimensional object transparency has transmittance $O(x,y)$, then the light amplitude in the frequency plane is the object spectrum, given by the Fourier transform of the object

$$F(\nu_x, \nu_y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} O(x,y) \exp [-2\pi i(x\nu_x + y\nu_y)] dx dy \quad (A1)$$

The spatial coordinates (x', y') in the frequency plane are related to the spatial frequency variables (ν_x, ν_y) by

$$x' = \lambda f \nu_x \text{ and } y' = \lambda f \nu_y \quad (A2)$$

If a filter with transmittance $H(\nu_x, \nu_y)$ is placed in the frequency plane, the filtered image is

$$I(x,y) \cong \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} F(\nu_x, \nu_y) H(\nu_x, \nu_y) \exp [2\pi i(x\nu_x + y\nu_y)] d\nu_x d\nu_y \quad (A3)$$

When $H(\nu_x, \nu_y) = 1$, the image is just the inverse Fourier transform of the (truncated) object spectrum; that is,

$$I(x, y) \cong O(-x, -y) \quad (A4)$$

KEYWORDS

optical spatial filtering

radioisotope scanning

radionuclide imaging

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Fig. 1-- Coherent light with wave length λ is diffracted by a periodic transparency at discrete angles $\pm \theta_m$ that are integral multiples of $\theta \propto 1/d = \nu$, the fundamental frequency of the periodic transparency. The resulting Fraunhofer diffraction pattern is the Fourier spectrum of the transparency. (See also Fig. 7).

Fig. 2 --A sinusoidal plane wave component of the object gives rise to light spots centered at $y = \pm f\lambda v$ in the frequency plane. Thus, the frequency components of any two-dimensional transparency are separated spatially in the frequency plane.

SPATIAL FILTERS

Fig. 3--Sharp cutoff filters are masks placed in the frequency plane to block unwanted sinusoidal components.

Fig. 4 --A low-pass filter eliminates the high frequency components with $\nu > 0.72$ cycles/cm in a sunburst pattern. Left--Unfiltered. Right-- Filtered.

Fig. 5 --The low-pass filter smooths a photoscan. Left--Unfiltered. Right--Filtered.

Fig. 6 --A lateral brain scan obtained in 90 seconds of scanning time contains artifacts due to noise, line structure, and distortion.

- A) anatomical structures
- B) unfiltered photoscan
- C) sharpened with a high pass filter, eliminating low frequencies $\nu < 0.16$ cycles/cm.
- D) the line structure has been removed with the filter shown in Fig. 7 (Lower).

Fig. 7 --The line pattern (upper) has the same spacing (lower) as the scan raster in Fig. 6B. Its frequency spectrum, (lower), was recorded on film and used to block the line structure in the brain scan to produce Figure 6D.