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ANALOG METHODS OF DATA STORAGE

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I. Introduction

The formation of a diagnostically useful image of the distribution of radioactive material that has been administered to a patient requires a radiation detector and a medium for storing the detector output, at least temporarily, for inspection and/or analysis by a physician. In most cases a permanent record is made of the stored image, to be used later for analysis or processing.

In general, the output pulses from the radiation detector may be transformed in various ways to provide a suitable input to the storage medium.

In digital systems, these pulses are counted, so that the stored image at each point consists of a discrete numerical value associated with a discrete neighborhood about the point.

In analog systems, the stored image at each point is represented not by a number, but by the magnitude of some physical entity averaged over a neighborhood about the point. The physical entity may be blackness of paper, film density, light intensity, electrical charge density, magnetic field strength, et cetera, the average magnitude of which can vary in an essentially continuous manner.

Both digital and analog methods of storage have advantages and disadvantages, so that the choice between them depends upon the requirements in particular applications, including how the stored image is to be utilized in the diagnosis. If quantitative information is required, or if the image must first be processed in some quantitatively precise manner, then digital storage is probably most satisfactory. On the other hand, if the diagnosis is to be based on a visual inspection of the image, with secondary significance attached to precise quantification, then analog storage may be most satisfactory.

Here, we wish to summarize briefly the characteristics of some analog storage media, with special consideration given to the problems of:

1.) extracting quantitative information concerning the distribution of radioactivity from the stored image.

2.) utilizing the storage medium itself as an on-line image processor.

II. Analog Media for Permanent Storage (Recording), and Techniques for Quantifying the Image

1.) Impact printing.--In 1951, Cassen et al. (1) introduced a scanning system that incorporated a mechanical tapping device which moved with the detector and imprinted a carbon mark on paper for each recorded pulse. This produced a life-size image that could be observed during the scanning procedure. The scanning speed was adjusted according to the count rate so that recorded marks would not overlap and produce uniform blackening over regions of high count rate. In addition, since the solenoid-driven tapper tended to become paralyzed at high counting rates, pulses from the detector were counted-down and only a preset fraction was recorded. This resulted in a very discontinuous, unsmooth image over regions of low counting rate.

The number of γ-rays detected over any area could, in principle, be determined by counting marks; however, the practice of interpreting the image on the basis of a subjective visual impression of any apparent abnormalities in the distribution of marks soon became routine. This practice has resulted in the tendency to regard analog storage and recording as essentially "non-quantitative."

To obtain a quantitative visual impression of the count rate over each region without counting recorded marks, the impact printing principle has been utilized more recently by Hine et al. (2) in a color recording system. In this case, the tapper strikes one of the eight color strips on a printing ribbon, the color at each point being determined by the output of a count rate meter. This use of multiple color recording increases the dynamic range of the system despite overlapping marks because the system can be calibrated so that each color (rather than the number of marks) corresponds to a known count rate.

To obtain a statistically valid selection of color, the counts must be integrated over some finite period. The integration time of the rate meter introduces a time delay in the color shifts between count rate levels. Since adjacent lines are scanned in opposite directions, this time delay causes a spatial displacement of recorded colors in opposite directions on adjacent lines. The resulting "scalloping" artifact is a disadvantage in any recording system that makes use of conventional passive RC circuitry to determine the local count rate during the storage operation. Tanaka (3) has recently suggested, however, that "operational" count rate meter circuitry can be used on-line to enhance images.

2.) Teledeltos paper.--The audible noise and limited response time of the mechanical tapper can largely be overcome by the use of a brief electrical spark to burn a mark on teledeltos recording paper, and this technique is widely used (4).

As with black and white impact printing, the degree of blackening per unit area increases in proportion to the count rate only as long as the rate is low enough (or the count-down factor large enough) to preclude overlapping of recorded marks. This is due to the fact that, on a local basis, such media are essentially binary in nature, the local state being either white or black. At counting rates high enough to cause overlap, the dynamic range of the storage medium is exceeded, and the image is essentially uniformly blackened. To some extent this effect can be reduced by recording smaller marks, and this can be achieved by reducing the spark current or duration.

Again, the necessity of recording non-overlapping marks means that individual marks can be counted for quantitative purposes.

3.) Photographic film.--If black and white film were used to record marks like those recorded by Cassen's impact printer or a teledeltos system, and if these marks were intense enough to saturate the film, then the storage capacities of these systems would be the same. Since for marks of this large size (compared to individual grains), film is capable of a continuous gradation of local blackening, and there is no need for recording such intense marks, the degree of blackening in the neighborhood of each point can be made to depend upon the total exposure due to overlapping marks which may not be individually countable.

In this case, it is variable film density at each point (rather than variable color) which extends the dynamic range of the storage system enormously. The use of color film could extend the dynamic range even further. In addition, film is capable of storing exceedingly small marks compared to either of the above-mentioned media.

Since photographic film is the most widely used medium for storing radioisotope images (5-9) its properties will be reviewed briefly. For a comprehensive treatment of photographic materials, see Mees (10).

(a) Characteristics of film (transparency): Ordinary photographic film consists of base material of cellulose or polyester on which a thin coating of a light-sensitive emulsion such as silver halide grains has been deposited. On exposure to light of sufficiently short wavelength (actinic radiation) some of these grains are rendered developable[*] in the sense that the silver halide is reduced to metallic silver on development. The result is that opaque grains of metallic silver will remain on the developed film for adequately[†] exposed silver halide grains. Unexposed grains are removed in the development process. The production of developable grains by exposure to light is described as the formation of a latent image. Here, we regard the latent image as a form of storage which yields a permanent record on development.

To the degree that the number of developable grains can be increased, the degree of blackening of the developed film increases with increased exposure to actinic light. The most common way of describing this relationship quantitatively is in terms of the so-called H & D curve, or characteristic curve, which describes the developed film density, D, as a function of the logarithm of the light exposure, E. Here, density and exposure are technical terms used to quantify the degree of film blackening and the light energy incident per unit area, respectively.

Exposure, E = Average Light Intensity X Time

If the light energy is delivered to the film by a pulsed light projector, which is turned on for a brief period for each stored event, then the expected

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[*] Whether or not a silver halide grain is "developable" depends upon the conditions of development. If the developer (a reducing agent) is sufficiently concentrated, and the development time is sufficiently long, even unexposed silver halide grains are reduced to metallic silver. Exposure to light greatly increases the rate at which the reaction proceeds.

[†] Only a small fraction of the silver halide molecules in a grain need be affected by the actinic light in order for the entire grain to be reduced to metallic silver or normal development. In this sense, the development process amplifies the effect of exposure to light. The affected silver halide is called a latent image center.

total exposure at each point is determined by the size, shape, intensity, and duration of projected light spots, as well as the number stored per unit area. This number is determined by the scanning speed, index width, and count rate. If, for a given scan, all of the physical parameters are held constant, the exposure to the film is simply proportional to the number of counting events observed at each point. This exposure results in a certain density in the developed film.

$$\text{Density, } D = \log[\text{Opacity}] = \log\frac{\text{Incident Light Intensity}}{\text{Transmitted Light Intensity}}$$

A typical characteristic curve, D vs. log E, is shown in Figure 1. If, for example, one projected spot, or one stored count, corresponds to one unit of exposure, and this produces a film density that is twice the fog level (see point A in Fig. 1), then 100 counts could be stored at the same place on this film (see point B) without saturation, which occurs when approximately 1000 counts are stored (see point C). The useful ranges of density and log exposure, ΔD and Δ log E, are ordinarily defined by the straight line portion of the characteristic curve, between points A and B. The slope of this segment is called the γ of the film, which is a measure of the rate at which density increases with respect to log exposure. Transparency materials are made with a very wide variety of characteristics, which provide a versatile and convenient form of storage.

It is evident from this curve that a nonlinear relation exists between Density and Exposure. However, linearity is not necessary for the purpose of extracting quantitative information concerning the distribution of radioactivity from the recorded image. For this purpose, it is necessary only that film density be a single-valued function of exposure; since exposure is proportional to the observed counts due to radioactivity, film density is then a single-valued function of observed activity.

The problem of quantifying the observed activity is in essence the problem of sensitometry, i.e., establishment of a one-to-one correspondence between observed film density and exposure. In general, this problem is complicated by the fact that film density is affected not only by exposure, but also by

exposure duration (and the possible failure of reciprocity),
the color of light used in the exposure,
the age and condition of the film,
the type, concentration, and temperature of the developer,
and, by the development time.

The variation of these factors virtually rules out the possibility of a fixed calibration scale that would associate an observed film density with fixed exposure value.

All of these sources of variation can be eliminated, however, by recording a calibration strip on the same piece of film used to record the image. To achieve this, a calibration step-wedge generator was built into the Argonne Cancer Research Hospital's brain scanning system (11, 12). This calibration system consists of a source of radioactivity (^{204}Tl, a .76 MeV β-emitter with a half-life of 3.6 years), a radiation detector (in this case, a Geiger tube), and a calibrated absorber that is moved between the source and detector by the horizontal motion of the scanning mechanism (see Fig. 2). As the absorber moves back and forth, the count rate from the Geiger tube covers the range from 100 cpm to 9,500 cpm in 26 steps of 20% increase. Pulses from this device are fed to the same circuits and light projectors used to record pulses from the scintillation detectors. These calibration pulses produce a step-wedge of densities due to known count rates on the same film used to record the brain scan, and for the same conditions of scanning speed and index width.

This calibration technique, which can be carried out either before or after the actual scanning procedure, permits quantitative determination of the count rate at each point on a brain scan to within about 20%. The comparison of film densities can be done with a densitometer, a closed circuit television system, or a flying-spot scanner to produce isodensity contours in black and white or color (13) (see Fig. 3).

Of course, determination of the count rate at each point on the recorded image does not always enable one to determine conveniently other quantitative aspects of the apparent distribution of radioactivity. For example, there is no convenient way of determining the total number of counts recorded within an arbitrary region of variable density from such an image. If such information is required for the diagnosis, digital storage may offer a more convenient means of obtaining it.

(b) <u>Characteristics of Photographic Papers</u>: The sensitometric properties of photographic paper can also be described by a characteristic curve, D, <u>vs</u>. log E. In this case, however, D refers to the <u>reflection density</u>. This quantity is defined as "the logarithm of the ratio of the evaluated portion, P_o, of the radiant flux incident on the sample to the evaluated portion, P_s, of the radiant flux reflected by the sample. Thus,

$$D = \log_{10}\left(\frac{P_o}{P_s}\right) = \log_{10}\left(\frac{1}{R}\right) ,$$

when R is the reflectance of the sample" (10).

For typical glossy papers, the useful ranges of density and exposure are considerably smaller than the corresponding ranges obtainable with transparency materials.

For recording the image from a cathode ray tube, convenient paperprint materials are the Polaroid films, such as Type 107. This material has a useful density range of $\Delta D = 1.58$, which corresponds to a log exposure range $\Delta \log E = 1.17$, or an exposure range $\Delta E \simeq 15$ to 1. This rather limited latitude means that considerable care must be taken to obtain a useful print; to some extent, this problem can be circumvented by bracketing the exposure.

In addition, this method of recording suffers some loss in contrast by the cathode ray tube. This is due to several factors such as light diffusion in the phosphor, internal reflections in the glass face plate, and low level persistent glow of the filament and phosphor (14).

III. Characteristics of Analog Media Required for On-Line Image Processing

For the purpose of storage alone, an ideal storage system might be thought of as one that could preserve perfectly the most probable position of origin of each detected γ-ray. (For an ordinary scanning system, this corresponds to the position of the detector axis at the time when each γ-ray was detected.) By recording very tiny marks, the analog media already discussed approach this ideal system.

It was recognized early, however, that the subjective visual quality of such recorded images might be improved to some degree by smoothing, which would reduce or eliminate the visibility of individual marks.

Such smoothing can be accomplished off-line in many ways: by viewing the image through a diffusing glass; by projecting the image slightly out of focus; by removing the viewer's corrective lenses, et cetera.

MacIntyre et al. (6) achieved the effect of "data blending" or smoothing by recording on film the out-of-focus spots displayed on a CRT. In the ACRH brain scanner, image smoothing is achieved by projecting a bell-shaped spot on film (12). In either case, these techniques can be thought of as a form of on-line processing of the detector output which is carried out during the storage operation and preserved in the recorded image when the film is developed. Any additional processing must be performed off-line as indicated in Figure 4 (upper).

The question naturally arises, "Can other types of processing, which are currently performed off-line, be made a part of the on-line processing, and carried out during the storage operation?" In particular, "Can image sharpening be achieved on-line?" so that the recorded image would be comparable in sharpness to images currently obtained by off-line processing with a digital computer (15-17), an optical spatial filtering system (18), or a flying-spot scanner (13). If so, then routine sharpening procedures might be performed most conveniently on-line.

Briefly, the answer to these questions is yes, provided that the on-line processor is capable of temporary storage and local erasure; that is, addition and subtraction (see Fig. 4, lower). To understand the basis of this requirement, it is useful to review briefly how such operations as image sharpening may be carried out with an off-line digital computer, since this method closely resembles the on-line analog methods to be described.

To sharpen an image that is represented by a matrix of numbers corresponding to detected γ-rays, one procedure is to convolute this matrix with a relatively small filter matrix, say 3 X 3, which consists of a positive value in the center, surrounded by a ring of negative values (see Fig. 5, left).

As the convolution is carried out by a digital computer, this filter function is weighted by the value of the unfiltered image at each point. The sharpened image is found by summing the contributions at each poont due to the weighted filter functions. This process involves serial operations in which positive and negative values are summed. Thus, both addition and subtraction are performed in the serial sharpening process.

Similarly, since the image of a radioisotope distribution is produced serially, by detecting and processing one γ-ray at a time, we might expect on-line analog sharpening to require the operations analogous to addition and subtraction; namely, storage and erasure, of some physical entity. In contrast, on-line smoothing requires only storage (addition of some physical entity.

To make the discussion of on-line image sharpening concrete, three examples of erasable analog media are described below, together with a brief explanation of how they might be used.

IV. Erasable Analog Storage Media and Techniques for On-Line Image Sharpening

1.) Photographic film, utilizing the Herschel effect.--In the preceding discussion of film, we mentioned the well known fact that exposure to light of sufficiently short wavelength renders some of the silver halide grains developable. The formation of this latent image on the undeveloped film was regarded as a form of storage operation, which resulted in a permanent record on development.

The fact that this latent image can be erased before development by exposure to light of longer wavelength than actinic radiation is perhaps less widely known, although the literature on the subject is extensive (10). This phenomenon is called the Herschel effect, after John Herschel, who made the discovery in the 1800's.

A product based on this effect is Kodak Autopositive film. Briefly, this material has been pre-exposed to blue light to form a uniform latent image that would produce a density of approximately .8 on development. It is commonly used to make positive copies of line drawings* by contact exposure to red or yellow light, which is of sufficiently long wavelength to erase the latent image.

The degree of erasure is determined by the exposure to long wavelength light much as the degree of storage is determined by the exposure to short wavelength light (although the exposure required for erasure is much greater). In addition, these operations can be performed repeatedly on the same undeveloped film.

Since storage and erasure are analogous to addition and subtraction, it would appear plausible that image sharpening can be performed on-line by projecting on pre-exposed, Herschel effect film, a spot that is blue in the center and red or yellow in the surrounding annular ring, for each detected γ-ray (see Fig. 5, right).

Kelly has made use of this effect to produce sharpened prints of transparencies (19). In this case, the chromatic aberration of the copying lens was used to produce the desired light configuration; that is, by focusing for a sharp image in blue light, a red ring about a blue center appears on the Herschel sensitive film.

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*This material is designed to make positive copies of high contrast transparencies, and is not well suited to applications in which a wide latitude is required.

For radioisotope imaging systems, a color television tube might be used as the source of red and blue light.

2.) Photochromic materials.--Although these materials do not depend on silver halide for photosensitivity, they can be darkened by exposure to ultraviolet light and erased by infrared light (14). As a consequence, they might be used in place of photographic film utilizing the Herschel effect as an erasable storage medium.

3.) Charge storage tubes.--In erasable photographic storage media, incident light photons produce low energy electrons that release other electrons trapped in latent image centers. Similarly, incident electrons of appropriate energy may produce this effect directly, without the conversion step from photons. However, if a beam of electrons is available directly, it is possible to take advantage of other electrical phenomena and process such an electron image without the intervention of a photographic latent image. The example to be discussed here involves electrical conductivity changes in semiconductor storage media, the common physical basis of charge storage tubes.

Commercially available charge storage tubes (CST) are able to convert electron signals to optical images for immediate viewing and evaluation, as are cathode ray tubes (CRT). But more importantly, in a CST, these electron signals may be temporarily stored, processed (enhanced), and then viewed before permanent recording or filming. All this can be done with analog signals, without conversion to numerical data.

The elements common to all CST are shown in Figure 6; a patterned source of electron charges (the electron signal), a medium for storage and recovery of the charges, and a means of transforming the stored charge into a structured beam of output electrons. Means of conversion of the input and output electrons to and from photons is also provided in some tube devices--as shown by dotted lines in Figure 6. The interaction between an input source of electrons and the storage medium is commonly known as writing, while that between a stored charge and the output electron signal is referred to as reading.

A very large number of tube types have been designed, according to different methods of modulating the writing and reading beams, of storing and transforming the charge patterns, and of arranging the tube elements (25,30). Nevertheless, it is useful to distinguish 4 basic varieties, according to whether light or electron signals constitute the primary inputs and outputs. (1) TV camera tubes are characteristic of the type with photon inputs and electrical outputs (26). (2) Those CST with electron inputs and visual outputs are often known as direct view storage tubes (DVST), and (3) those with both inputs and outputs of electron signals as electrical output storage tubes (EOST) (24,27). (4) Charge storage tubes with visual inputs and outputs are variously called image storage (30) or storage image (29) tubes.

The capabilities of charge storage tubes for off-line image processing by analog (or digital) methods have been described (20,22,23,29). For on-line processing, however, somewhat different considerations apply. It is necessary to choose a writing method and storage mechanism so that a bipolar distribution of charge can be deposited in the neighborhood of a point of the storage medium whenever a radiation event is detected. This arrangement is analogous to the blue and red spot of light used to produce the Herschel effect on a photographic latent image.

A bipolar distribution of charge may be written onto a storage medium by the "redistribution effect" (25). As shown in Figure 7, a redistribution of charge within a solid insulator occurs when bombardment by an incident electron beam produces secondary electrons (by collisions), some of which have the proper direction and sufficient energy to escape from the surface. The number of escaping secondaries varies with the energy of the primary electrons, the properties of the storage medijm, and the electric field at the solid surface. With a sufficiently positive difference of potential between the surface and a nearby collecting electrode (not shown), a larger number of negative electrons will leave the storage medium than arrive in the primary beam. In that case, the storage material is left with a net positive charge at that point, assuming sufficient insulation from other (neighboring) sources of electrons.

On the other hand, if the electrical potential close to the storage surface is made a trifle negative, then some escaping secondary electrons of low energy will be turned back to the surface and recaptured, as shown in Figure 7. A simple control grid positioned nearby, and connected to an adjustable source of voltage, can provide the necessary electric field. In fact, in commercial CST, such a control grid is often provided to eliminate the redistribution effect (by means of a positive potential) when it might distort an otherwise uniform charge distribution required for certain applications.

These electrons, returned to the storage medium by the redistribution effect, constitute a negative charge added to the neighborhood of a region left positive by their departure. Thus, a bipolar charge distribution has been created at a point chosen to represent the position of a detected radiation event. The final shape of this point source response function may be electrically adjusted by prior variation of the relative potentials between primary electron source, storage surface, control grid, and collector electrode, and will be a function of their relative position, shape and material. A variety of storage materials is commercially available for these purposes, in both solid and mesh configuration, for selection of desirable parameters of sensitivity, noise, resolution and storage times.

An appropriate source of electrons must be chosen for incorporation of a CST, with the on-line capability of a bipolar aperture function, into an existing radiation detection system. In most systems position information about the probable location of the radiation source is available from the detector. For example, in scintillation scanners, the source is expected to be on the collimator axis, or in Anger type cameras the location is computed simultaneously with detection. In either case it is sufficient to provide a single source of electrons in the CST, such as an electron gun of the CRT type. Electrons from this source may be guided to the proper location of the storage medium by electric or magnetic deflecting fields which correspond to position information about the radiation event.

For the case where detector scintillations represent the input to an image intensifier, without further position information for each radiation event (31,32), a CST must be chosen with a photon sensitive input. TV camera tubes, for example, preserve the location of an incident radiation event on the input photocathode, and the photoelectrons from this converter are accelerated to the corresponding position of the storage medium. A good match between areas of output phosphor on an image intensifier and input photosensitive surface of a CST is available from commercial sources.

Finally, the choice of output for a CST is again to be made in the context of overall system requirements. If visual information is not needed at this location then electrical output signals, representing the algebraic summation of charges on the storage medium, can be provided by a scanning electron beam from presently available commercial tubes of the EOST variety. (They are commonly used in TV scan conversion.) In fact, a single electron gun can serve for both reading and writing, if the time requirements between input and output signals are not too critical (24). However, CST are also available in which the output beams of electrons are sent directly to phosphor surfaces, showing immediately the on-line progress of image accumulation. In general, there is adequate flexibility among commercial CST to meet the common requirements of radiation imaging systems.

V. Conclusions

Photographic film is currently the most widely used and generally satisfactory analog storage medium for radioisotope imaging systems.

The calibration of film, to obtain a quantitative measure of the detector output at each point, can be accomplished conveniently with a step-wedge generator. More complex quantitative information, such as the number of detected radiation events within an arbitrary area, is not easily obtained from analog storage media.

Although image smoothing is performed on-line routinely, by projecting overlapping bell-shaped spots on film, image sharpening is currently performed off-line. It appears that image sharpening could be performed on-line by a storage medium capable of accepting a bipolar input function, consisting of a central positive region (where addition, storage, or increase of some physical entity occurs) and a surrounding negative region (where subtraction, erasure, or decrease of the physical entity occurs). Photographic film (utilizing the Herschel effect), photochromic materials, and charge storage tubes have this capability.

In attempting to determine the particular situations under which on-line sharpening might be desirable, and safe, all of the usual precautions against an <u>a priori</u> choice of image manipulatives apply.

VI. References

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VII. Figure Legends

Figure 1. Typical characteristic curve for photographic film. The exposure required for density B is 10^2 times that required for density A.

Figure 2. Film calibrator consists of a line source of ^{204}Tl and detector separated by a step-wedge absorber designed to produce count rates from 100 to 9,500 cpm in 26 steps of 20% increase, as shown in Figure 3. (Reproduced with permission of the Journal of Nuclear Medicine.)

Figure 3. Left: Smoothed brain scan produced by overlapping bell-shaped spots. Calibrated step-wedge recorded on the same film permits quantitative determination of the count rate at any point.

Right: Isodensity (isocount) contour plots, which can also be produced in color.

Figure 4. Upper: Image smoothing is routinely performed on-line, and image sharpening off-line.

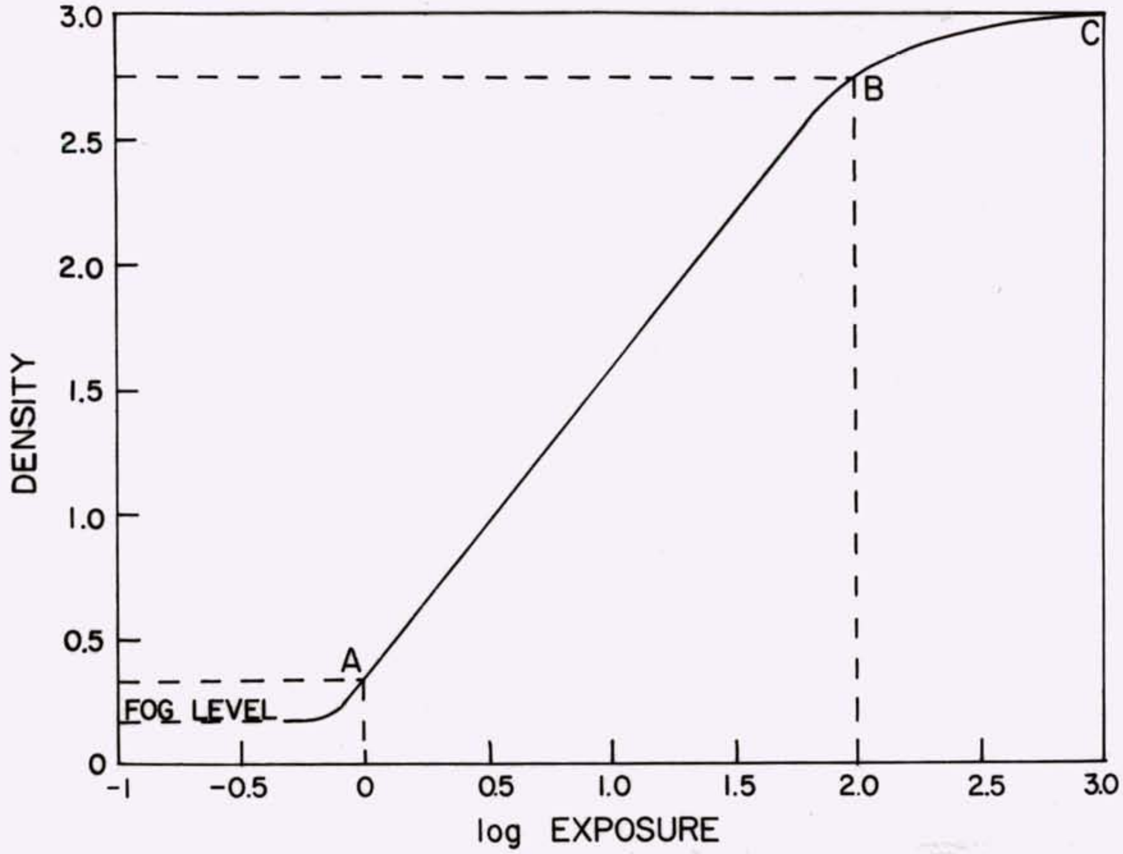
Lower: If the storage medium can accept bipolar inputs, for the addition and subtraction operations required for image sharpening, then sharpening also can be performed on-line.

Figure 5. Left: Cross-section of a typical filter function used by a digital computer for image sharpening.

Right: Cross-section of the projected light spot required for on-line image sharpening utilizing Herschel sensitive film. Blue light increases, and red light decreases the latent image density.

Figure 6. Input-output relations for charge storage tubes.

Figure 7. Bipolar configuration of charge results from the redistribution effect. This is analogous to the configurations in Figure 5, and permits on-line image sharpening with a charge storage tube.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0
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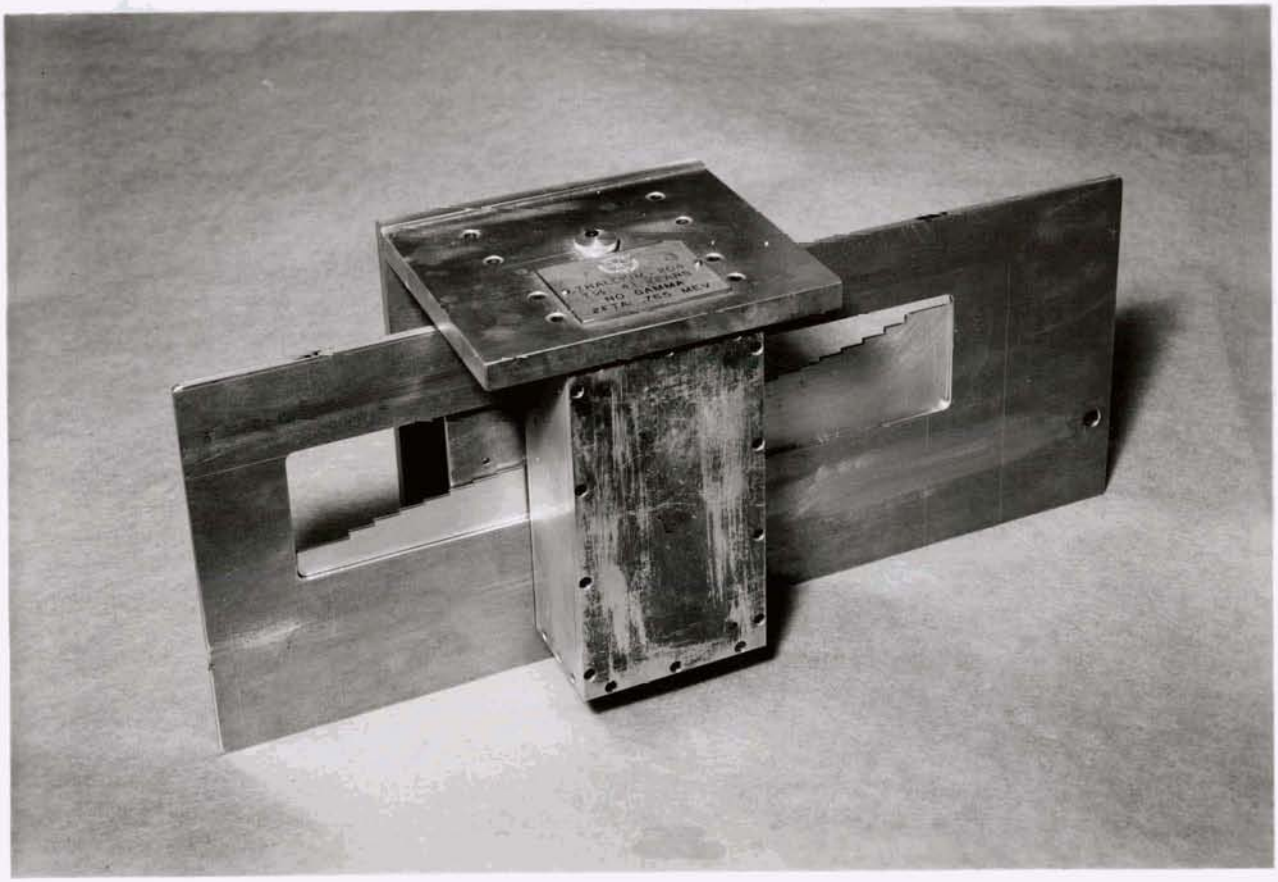
1.5
2.0
2.5
3.0
log EXPOSURE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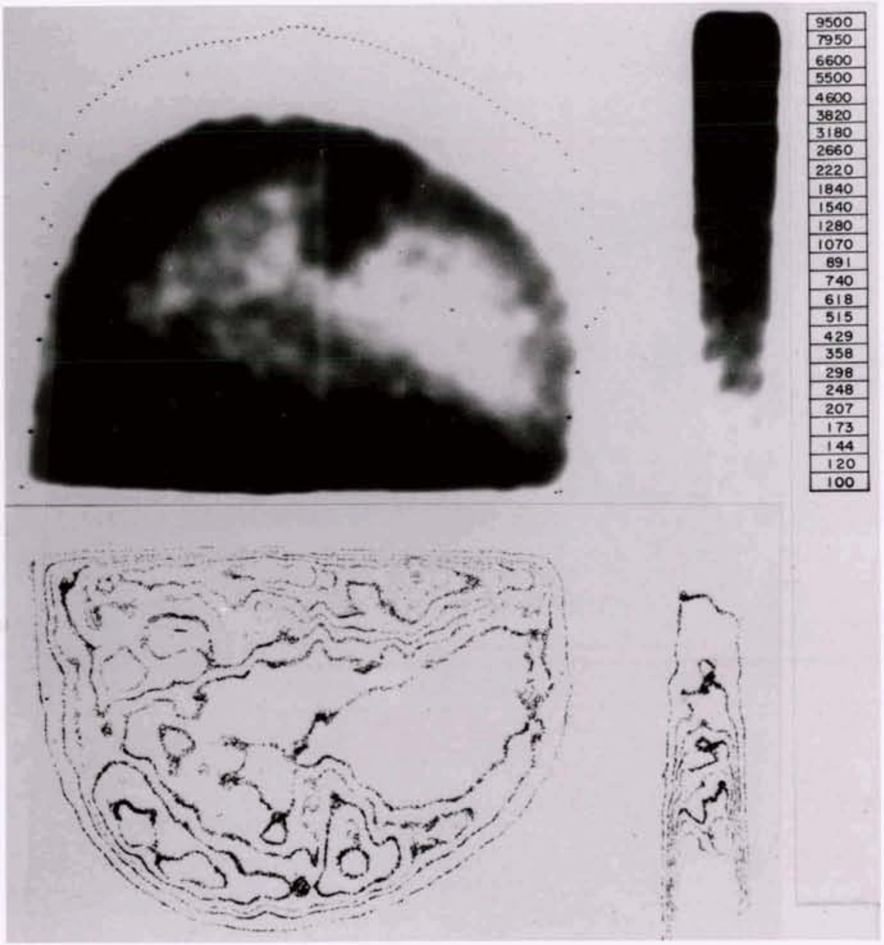
ZETA 765 MEV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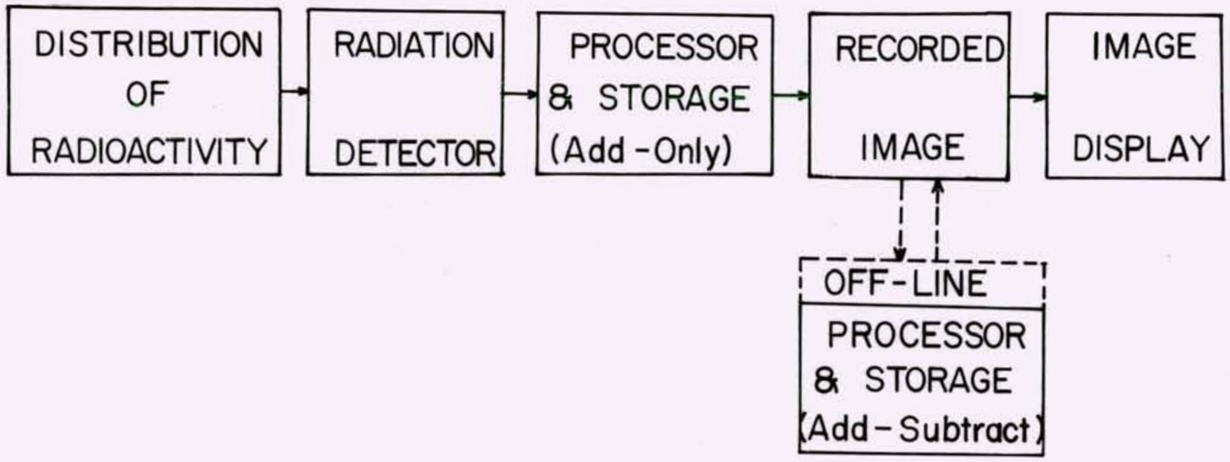
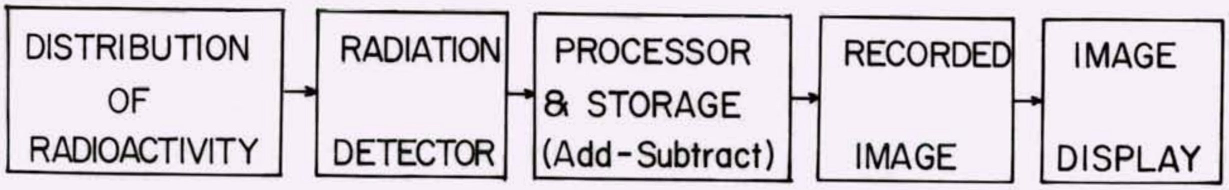

DISTRIBUTION OF RADIOACTIVITY
RADIATION DETECTOR
PROCESSOR & STORAGE (Add-Only)
RECORDED IMAGE
IMAGE DISPLAY
OFF-LINE PROCESSOR & STORAGE (Add-Subtract)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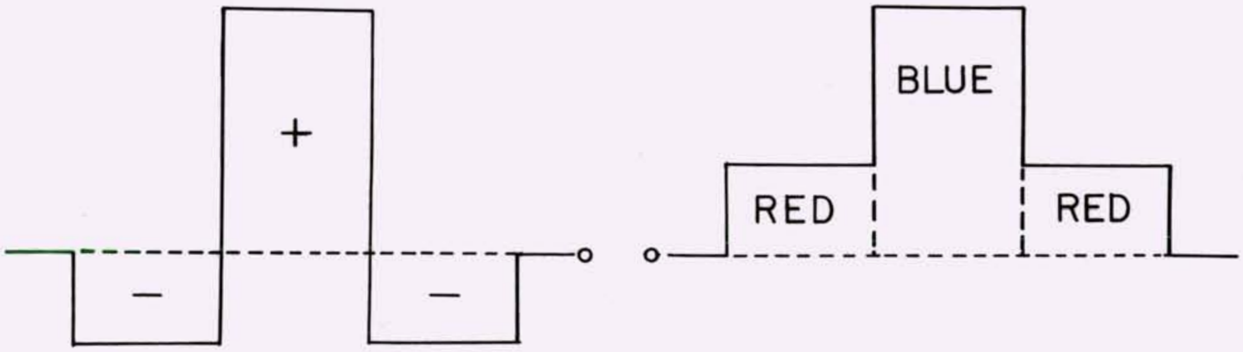
RADIATION DETECTOR
PROCESSOR & STORAGE (Add-Subtract)
RECORDED IMAGE
IMAGE DISPLAY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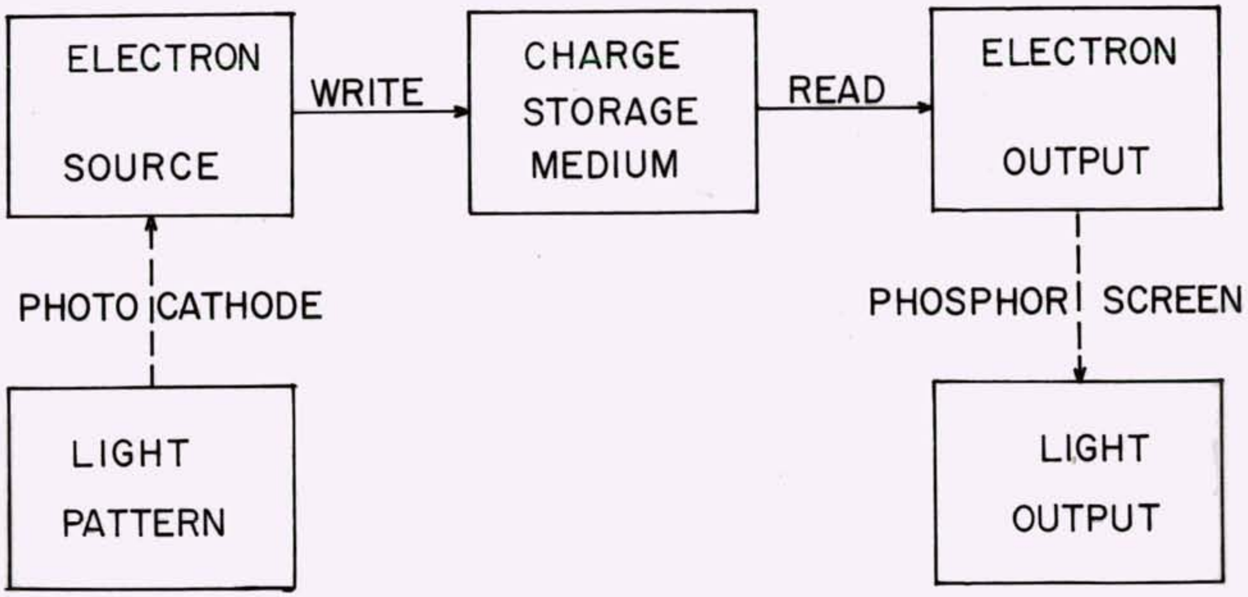
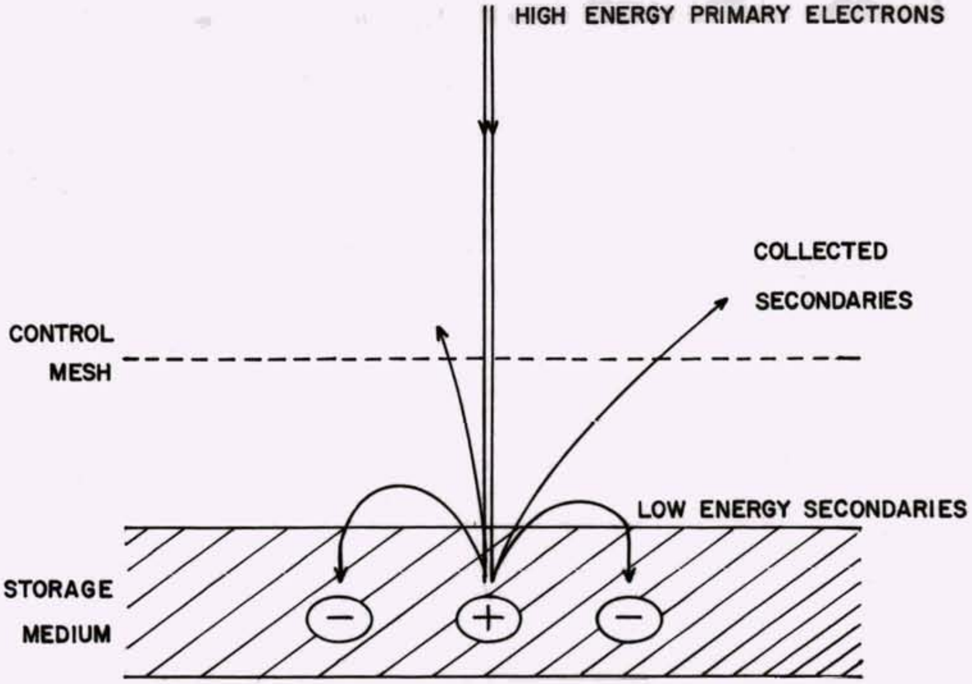
−
−
BLUE
RED
RED



CHARGE STORAGE TUBES



Redistribution Effect