DIGITAL AND ANALOG PROCESSING OF ANGER CAMERA DATA WITH A DEDICATED COMPUTER—CONTROLLED SYSTEM

William L. Ashburn, Kenneth M. Moser and Michel Guisan*

University Hospital of San Diego County, San Diego, California

In most nuclear medicine laboratories radionuclide images are recorded on x-ray or other types of photographic film because of the convenience of storage and display. Although a variety of photographic techniques can be used to improve the diagnostic quality of the recorded film image, most of these methods require the operator to preselect the necessary photographic factors based on counting-rate characteristics noted over the organ of interest. Alternative methods assume that a reasonably satisfactory image has been obtained which can be further augmented in a variety of ways including rescanning in color (*1*), rephotographing on closed-circuit television (*2*), or processing film densitometric readings of the original image (*3*). Common to all of these methods is the fact that the original recording is made on photographic film which, depending on the type of film used, is often rather limited in its dynamic range, and the recorded densities are seldom linear with respect to the true regional counting rates. This is particularly true of the routine images obtained from the popular scintillation cameras where the image is normally recorded on a rather high-contrast Polaroid film (*4*).

A number of reports have appeared (*5–11*) which describe alternative methods for image storage and processing in which the original data are recorded digitally either on paper punch tape, magnetic tape or other similar storage media and are often processed by a digital computer. These data can then be reconstituted in a variety of image formats such as intensity modulated oscilloscopic images or as two-dimensional patterns in which the regional counts appear as different typewritten characters.

In this paper we wish to comment further upon the advantages of recording radionuclide images in a digital format for subsequent computer processing, analysis and presentation for permanent photographic recording and to describe a commercially available system† which was adapted to a standard Anger scintillation camera for this purpose.

† 50/50 MED Digital Image and Processing System provided through the courtesy of Nuclear Data Inc., Palatine, Ill.

METHOD

The operation of the Anger scintillation camera is well known (*12*). In the system discussed in this report, the camera is unaffected by the operation of the additional components (Fig. 1). Three signals are required from the scintillation camera to transfer data to the digital system. The x- and y-positioning signals, normally used to align the electron beam of the scintillation camera oscilloscope, are digitized by a pair of high-speed analog-to-digital converters. An unblanking signal is also required from the camera to allow the digitizing process to proceed only upon final placement of each detected scintillation which, of course, has met the proper pulse-height requirements set by the scintillation camera analyzer circuits. The digitized x- and y-coordinates are used to direct each incoming count to the proper address in the magnetic-core memory of the storage and display unit, corresponding to the position in the detector where the scintillation occurred. Thus when the 64 $\times$ 64 address matrix is used, a scintillation occurring in the geometric center of the detector adds one count to digital address $x = 32$, $y = 32$. Similarly, using a 32 $\times$ 32 address matrix this same location would be represented as $x = 16$, $y = 16$. The total core capacity of the storage and display unit is 8,092 discrete addresses. This means that two 64 $\times$ 64 or eight 32 $\times$ 32 address matrices (frames) are available. The maximum number of counts that can be accumulated in each discrete address is 4,096, being limited by the 12-binary bit capacity of the core memory.

The core memory contents are displayed on an oscilloscope which allows essentially continuous inspection of the recorded data as well as Polaroid pictures to be taken for a permanent record. Each displayed dot represents a discrete address in the core memory, and the intensity of each dot is proportional to the counts accumulated in that particular address for the period recorded. A range switch is

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For reprints contact: William L. Ashburn, Div. of Nuclear Medicine, University Hospital of San Diego County, 225 W. Dickinson St., San Diego, Calif. 92103.

* Present address: 1083 Mezieres (Vaud), Switzerland.

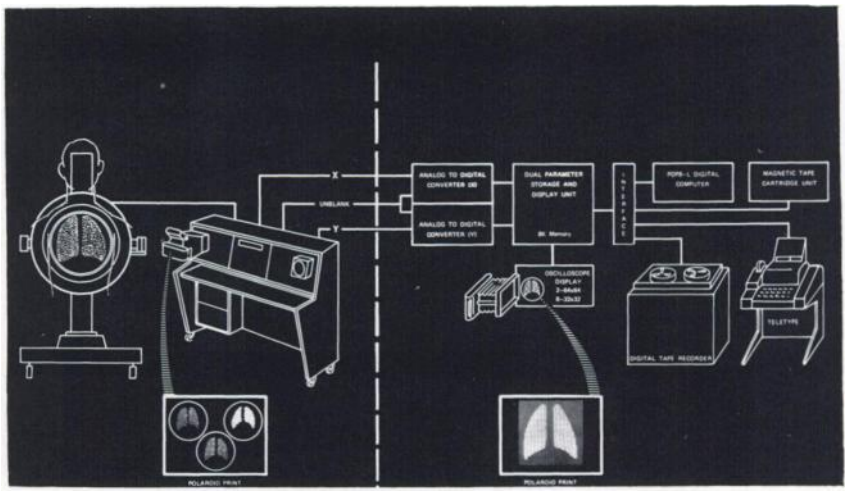

FIG. 1. Computer-controlled digital recording and analytical system used with Nuclear-Chicago Pho/Gamma III scintillation camera (shown on left).

provided so that full intensity can be given to each address with a total count of 64, 256, 1,024, 4,096 or values within these limits. Addresses with fewer counts are displayed with proportionally less intensity, thus providing a continuum of intensities. Selection of one of these ranges has the general effect of extending or reducing the contrast scale of intensities. The overall brightness of all displayed addresses can either be continuously varied or the relative intensity of low versus high count addresses can be adjusted with an "intensity" control. Reduction of intensity by adjusting this control disproportionately reduces the intensity of the low count addresses with respect to the high count addresses, thereby increasing contrast.

The display can also be modified by lower- and upper-level discriminators, which are continuously variable, allowing the intensities of the low or high count addresses, respectively, to be reduced to a very low background intensity level. These controls further function to exclude these low or high count addresses from being integrated during the area-of-interest integration modes. Areas selected for computer integration are brightly intensified so that each address within the region of interest is easily identified. Areas for integration can be represented as a single address or any combination of adjacent addresses up to the full image matrix of 64 $\times$ 64 addresses, thus providing areas-of-interest in the form of lines, squares or rectangles. The area-of-interest for integration is easily moved over the displayed image by adjusting two variable controls. The height and width of the area-of-interest are adjusted by a second pair of controls. Irregular shapes for integration can be chosen by selectively including or excluding high or low count addresses by adjusting the discriminators described above. Other display modes are possible, including isometric, isometric with reverse axis, single x and y profiles or individual x or y slices (single lines).

In many respects the storage and display unit operates as any dual-parameter multichannel analyzer used in physics, or more recently with scintillation cameras (*13–17*). Noteworthy, however, is the fact that "cycling time" has been reduced to approximately 3 μsec to handle the high counting rates available with the scintillation camera. In addition, read-write functions have been highly modified so that one 64 $\times$ 64 frame can be recorded (stored) while the second 64 $\times$ 64 frame is read out to a digital magnetic tape recorder or other storage device. Further switching modifications have been made to allow simultaneous read-write routines in the 32 $\times$ 32 format using a high-speed digital magnetic tape recorder (45 in./sec, 800 bits/in.) so that up to 14 frames/sec can be recorded with no deadtime (0 dump time) between frames.

Although all of the data storage and transfer functions can be manually controlled, this system was designed in such a way that a small general-purpose digital computer (PDP-8L, Digital Equipment Corp.) with a core capacity of 4,096 is dedicated to these functions. Complete system interfacing and computer programming are used so that all instructions are initiated at the keyboard of the teletypewriter. The computer core memory is not used to store the incoming data from the scintillation camera but is used to operate upon the data stored in the core memory of the storage and display unit. The complete program options (supplied by the manufacturer) are too numerous to discuss, and the reader is referred to the manufacturer's product brochure for details. Essentially all arithmetic functions are provided. Thus all addresses of any frame can be modified by the addition, subtraction, multiplication or division of a constant value. Similarly, one frame can be added to or subtracted from another frame on an address-by-address basis. In a similar manner, one frame can be multiplied or divided by any other frame. Additional computational subroutines include

statistical smoothing of neighboring addresses, correlation for inhomogeneities in detector response, isocount contour determinations and others. One of the important features is a variety of dynamic recording and playback analytical programs that will be described in detail in future presentations.

Recorded frames are identified with digital "tag words" selected by the operator through the teletype keyboard before transfer of the recorded frame to magnetic tape. An automatic search routine finds the "tagged" frame requested so that it can be displayed on the oscilloscope, read out by the teletypewriter or digitally transferred to paper punch tape or magnetic tape in the cartridge cassette. The magnetic tape cartridge cassette unit also allows computer program or subroutine changes to be made in seconds.

Although the digital computer is "dedicated" by interfacing to the scintillation camera, it can be used separately just as any other small general-purpose computer. Thus any number of noncamera-related operations could be carried out. Indeed, the entire DEC (Digital Equipment Corp.) library is available.

RESULTS

The analog display of the data stored in the core memory of the storage and display unit can be modified during presentation either by continuous adjustment of the various hardwired components of the system or by computer augmentation of the data on a nondestructive basis.

In Fig. 2 the original scintillation camera image of a lateral ^{99m}Tc-pertechnetate brain study was compared with the 64 × 64 data display recorded for the same period of time. In this case, contrast was modified slightly by the "intensity" control of the storage and display unit, causing de-emphasis of low count areas to an extent greater than high count areas. In this way, the abnormal accumulation of the tracer in the parasagittal lesion was more easily recognized than in the original camera scintiphoto. Contrast was further modified by using the isocount contour computer program. All addresses in the core memory which contained less than 6% of the counts contained in the highest count address (determined by the computer after sampling all addresses and designating this address as 100%) were excluded from the display. For final presentation, all remaining addresses (6%–100%) were further intensified. The two available 64 × 64 memory halves of the storage and display unit were used for this operation, allowing the unaltered data to reside in the first half of the memory and the manipulated data to be placed by computer into the second half. Usu-

FIG. 2. Metastatic adenocarcinoma visualized (arrow) on gamma camera scintigram (A) compared with 64 × 64 display (B) and following contrast enhancement using isocount computer routine (C).

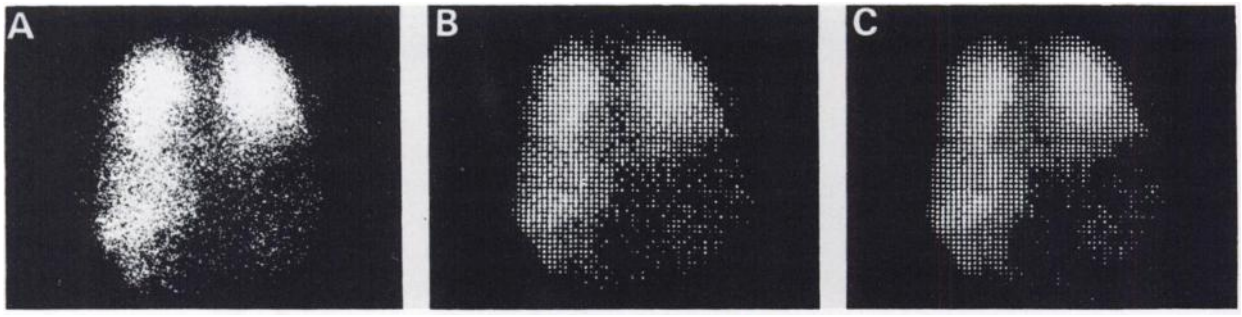

FIG. 3. Gamma camera scintigram (A) suggesting multiple areas of reduced perfusion, secondary to bullous emphysema. 64 × 64 display (B) and computer "smoothed" display (C) are shown for comparison.

FIG. 4. 64 × 64 display of ^{133}Xe lung transmission study showing mediastinal outline (A) was added by computer to ^{99m}Tc MAA left coronary artery perfusion study (B) to obtain composite (C) showing the extent of a myocardial perfusion abnormality (arrow) involving the antero-lateral aspect of the heart (see text).

ally contrast modification has been best performed under both hardware and software control, thus providing an infinite variety of display possibilities.

In Fig. 3 the original scintillation camera pulmonary scintigraph using ^{131}I-macroaggregated human serum albumin was compared with the 64 × 64 data display recorded for the same period of time. Both of these images demonstrated to an equal degree the multiple regional perfusion abnormalities which were secondary to bullous emphysema. Since a divergent collimator was used so that both lungs could be imaged simultaneously on the 10-in. useful diameter of the detector, each address represents a volume of lung approximately 0.6 × 0.6 cm by some undetermined depth. Without destroying the original stored data, the image was further modified using the "smooth" program in which the contents of each address were modified by the contents of all adjacent addresses according to a fixed software formula. While the end result of this type of image presentation is similar to defocusing the dots on the original display or to placing a piece of ground glass over the original image, the numerical printout of this stored data also reflects the smoothing operation performed by the computer.

The ability to add one frame of data to another is illustrated in Fig. 4. The patient, at the time of coronary angiography, had received an injection of a small number of macroaggregated human serum albumin (MAA) particles labeled with ^{99m}Tc (150 μCi) into the left coronary artery. Following removal of the catheter, a scintiphoto of the MAA distribution in the myocardium was made and simultaneously recorded in one 64 × 64 memory half of the storage and display unit. Without reference markers or other identifying features, we would have great difficulty in determining the true lateral extent of the left heart border. Therefore, a ^{133}Xe sheet transmission source was placed beneath the patient and a lung transmission image was recorded in the second memory half. The scintillation camera pulse-height analyzer was, of course, adjusted for the photon energy of ^{133}Xe and the patient was not moved between the two recordings. Both of the frames were transferred to magnetic tape for permanent storage. At a later time, the ^{99m}Tc-MAA myocardial perfusion frame was searched for (using its "tag" word) and transferred back into one memory half of the storage and display unit. Similarly, the ^{133}Xe transmission study was transferred to the other memory half. The computer-produced sum of these two images is shown in Fig. 4 and clearly demonstrates that there was an area of reduced myocardial perfusion involving the antero-lateral border of the heart as represented by the void of activity between the heart and the medial aspect of the left lung. This abnormality was confirmed both by coronary arteriography and by left ventricular angiography in which an antero-lateral area of dyskinesis was associated with occlusion of the marginal branch of the circumflex artery.

The value of the computer subtraction mode is illustrated in Fig. 5. In one 32 × 32 frame (one of eight available 32 × 32 units of core memory) a 15-min recording was made with a pulse-height discriminator of the scintillation camera set for the energy of ^{75}Se. In a second 32 × 32 memory division, a 45-sec exposure was made with the scintillation camera set for the energy of ^{99m}Tc. The patient had been previously given both ^{75}Se-selenomethionine (200 μCi) and ^{99m}Tc-sulfur colloid (1 mCi) intravenously. The data acquisitions were made sequentially without moving the patient between the recordings. Subtraction of the ^{99m}Tc-sulfur colloid frame of data from the ^{75}Se-selenomethionine frame was not initially attempted because of different count accumulations in these two recordings. To correct for these differences, an area-of-interest integration was performed over comparable regions of the liver as identified on both original recordings. In this case, the ^{99m}Tc-sulfur colloid frame had relatively more counts than the ^{75}Se-selenomethionine frame, which required reduction of all addresses in the sulfur colloid frame by a constant divisor. Following this modification, the two frames could be subtracted, resulting in a markedly improved image of the pan-

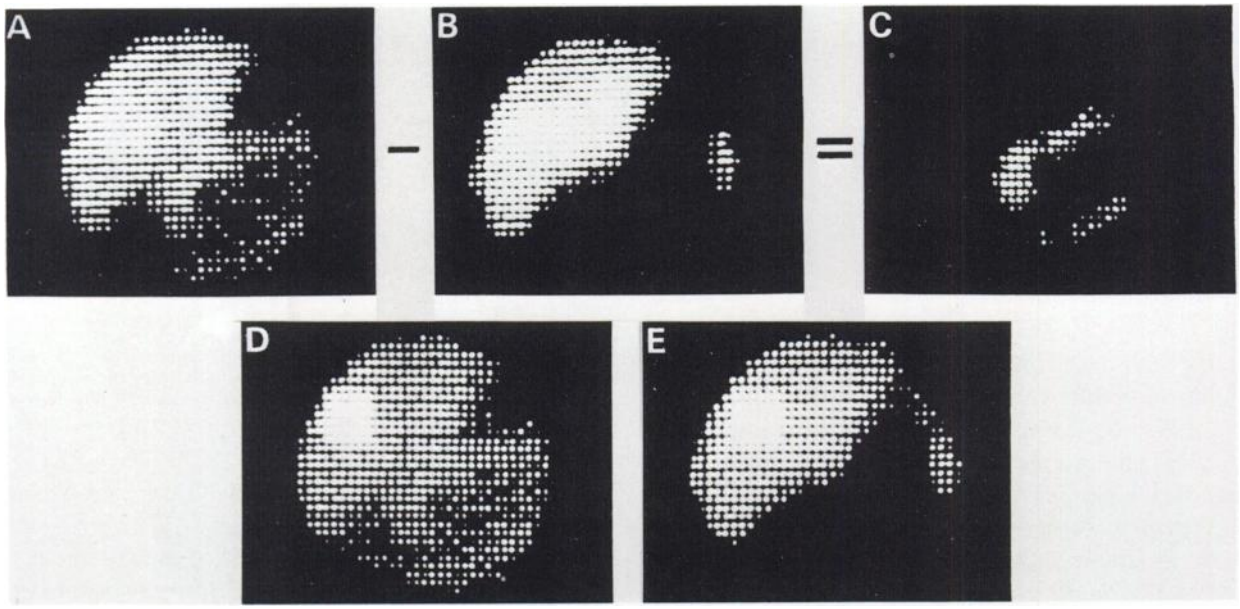

FIG. 5. Subtraction of ^{99m}Tc-sulfur colloid 32 × 32 data frame (B) from ^{75}Se-selenomethionine frame (A) by computer-produced image of pancreas (C) unobscured by overlying radioactivity in liver. Areas of interest for computer integration are shown (D&E) as brightly intensified addresses (see text).

creas, it being the "dissimilar" region of accumulation. The fact that zeros and negative numbers were not displayed explains why the spleen (also being a "dissimilar" region) is not displayed on the "subtracted" image.

The relationship between regional pulmonary ventilation and perfusion in the upright subject is illustrated in Fig. 6. The ventilation study was digitally recorded following the inhalation of a single breath of ^{133}Xe. Following "washout" of the radioactive inert gas from the lungs and without moving the patient, ^{133}Xe dissolved in sterile saline was injected through a central venous catheter into the superior vena cava to demonstrate the regional distribution of pulmonary blood flow. The even distribution of the inspired gas was seen both in the unmodified presentation and upon totaling (horizontally), line by line, a five-address-wide slice from apex to base and displaying this as counts plotted against lung region. In a similar manner, the relative underperfusion of the apical regions due to the upright position during injection was clearly demonstrated by a plot of the counts from apex to base totaled horizontally along a comparable vertical slice. To display the relationship of ventilation (V) to perfusion (Q) in similar regions of the lung from apex to base, ventilation-perfusion ratios (V/Q) were determined on an address-by-address basis by the computer by dividing the ventilation data recorded in one 64 × 64 frame by the perfusion data recorded in a second 64 × 64 frame. The relative underperfusion of the apices in contrast to the more even distribution of ventilation was most clearly depicted by the V/Q profile where these values were plotted against lung region. Had the subject been studied in supine position, the V/Q profile would have more nearly approached a straight horizontal line. For a complete discussion of ventilation-perfusion relationships, the reader is referred to the work of Newhouse *et al* (*20*) where the techniques and assumptions used are described.

The normal distribution of pulmonary blood flow, as indicated by the distribution of ^{131}I-macroaggregated human serum albumin injected in the supine position, is shown in the top row of Fig. 7. The isocount contour mode was used to more clearly demonstrate the pattern of blood flow throughout the lungs (Fig. 7B). However, the relative distribution from apex to base was best depicted by a totaled slice, five addresses wide, displayed as counts plotted vertically against lung regions plotted horizontally. A similar method was used to relate the regional distribution of blood flow in a patient with elevated pulmonary venous pressure secondary to mitral stenosis (Fig. 7-bottom row). In this case, there was a "reversal" of the perfusion gradient, i.e., greater blood flow to the upper lung zones, which, although seen on the unmodified display, was more clearly demonstrated on the isocount contour and count profile displays. While the teletypewriter printout of these totals would have been less dramatic, this data could be used to predict the degree of pulmonary venous hypertension (*21*).

A patient with recurrent hemoptosis and a normal

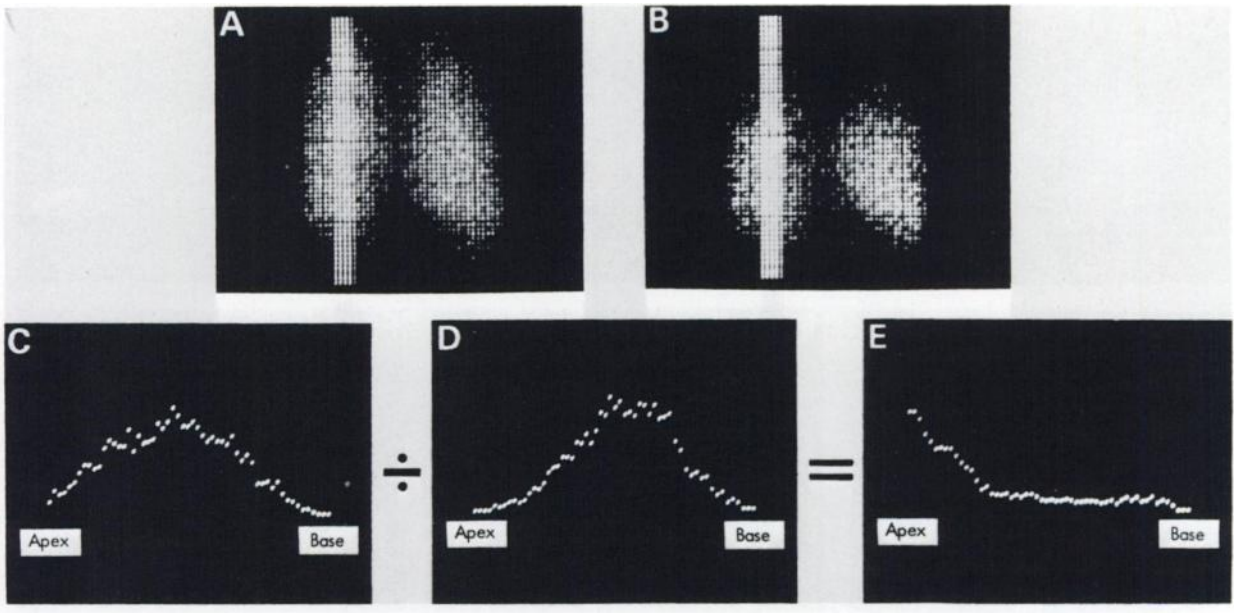

FIG. 6. Verticle slices from apex to base chosen from identical lung regions of ^{133}Xe ventilation (A) and perfusion (B) examinations in upright subject. Count profiles of ventilation (C) and perfusion (D) show relative reduced perfusion of upper lung zones due to upright positions during injection. V/Q profile (E) produced by computer division of frame C by D.

chest x-ray was evaluated on the computer-controlled system. In this case the counts accumulated in the center five addresses along the vertical axis of each lung in the ^{133}Xe ventilation study, were totaled by the computer and the results displayed on the oscilloscope as described in the preceding cases. Although one could appreciate that there was a relative diminution of ventilation in the right apex as viewed on the original ^{133}Xe inhalation scintiphoto, the relative magnitude of this difference was better appreciated on the count profile display. In addition to the generalized reduction in ventilation in the right apex there was a small peripheral segment noted where ventilation was further diminished. This was not readily appreciated on the original scintiphoto of the first breath of ^{133}Xe, nor on the comparable 64×64 display but was strikingly obvious on the modified display where low count addresses were reduced in intensity by adjusting the lower count level discriminator. This regional ventilatory defect was further documented by a prolonged "washout" of the ^{133}Xe from this segment and at the time of surgery where multiple small cysts were found.

DISCUSSION

Our ability to recognize abnormal patterns of radiopharmaceutical distribution depends on a number of factors. One fundamental requirement is that sufficient contrast exist between abnormal regions and adjacent normal areas. In many cases, increasing the optical contrast between high and low counting-rate regions can significantly increase the detectability of abnormal areas. This is done, however, often at the expense of producing images which preserve the subtle differences in counting-rate distribution so important in the overall appraisal of pharmacodynamics. Most often, a compromise must be made between these extremes so that a good image is usually one in which contrast is enhanced without destroying data from the low count areas. With the system presented in this report, contrast enhancement is accomplished in a variety of ways without destroying the original data. However, we do not proceed with contrast enhancement until the viewer has evaluated the original data in an "unaltered" format in which both low and high counting-rate information are displayed. By increasing contrast excessively, one can, of course, permit a significant lesion to escape recognition. Increasing contrast also tends to intensify counting-rate differences which result merely from normal anatomical variations or from poor count statistics resulting from insufficient counts.

Recognition also depends on our familiarity with the normal "scan" anatomy which can occasionally be helped by including other anatomical structures or appropriate markers on the final image. With the system described we have found it quite helpful, in a number of instances, to add separately recorded images one upon the other so that familiar anatomical landmarks can be used to outline the extent and location of pathological defects. Conversely, too much overlying anatomical information can make interpretation difficult, if not impossible. Obvious

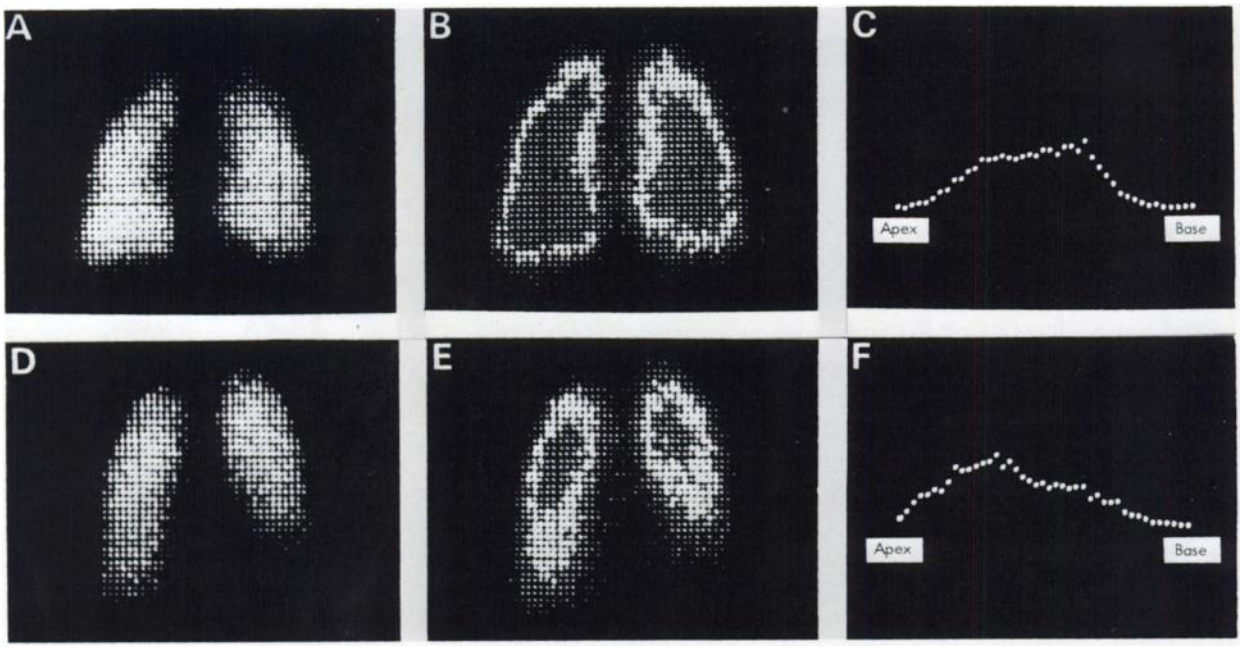

FIG. 7. Top row: Normal ^{131}I-MAA perfusion distribution (A), more clearly demonstrated as isocount contour (B) and as five-address-wide count profile from apex to base (C). Bottom row: Patient with mitral stenosis with under-perfusion of lower lung zones due to pulmonary venous hypertension. Isocount contour (E) and count profile of left lung (F) demonstrate perfusion abnormality.

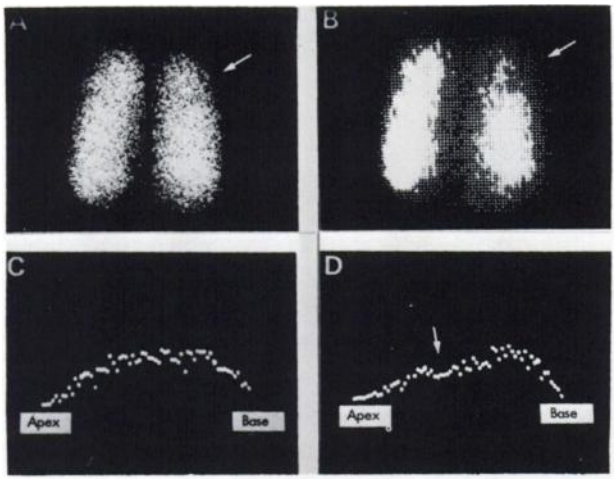

FIG. 8. Scintigram (A) following inhalation of ^{133}Xe gas failed to reveal focal ventilatory defect in right apex (arrow), shown clearly on modified 64 × 64 display (B) and count profile of right lung (D). Normal count profile of left lung is shown (C).

examples of this include the difficulty in visualizing the pancreas with ^{75}Se-selenomethionine (see Fig. 5) where the pancreas tends to be obscured by the overlying accumulation in the liver.

Recognition of abnormal patterns is made more difficult when insufficient counts are recorded for good image statistics. While the obvious solution is to obtain sufficient counts, there are situations in which the ability to add one frame of data to a second frame of data (recorded in the same position) can effectively increase the total usefulness of the image. This is particularly helpful in studies of ventilation and perfusion with ^{133}Xe in which sequential 5-sec frames of data can be recorded while the patient is holding his breath. Since it is quite impossible to predict beforehand the length of time that any patient can remain apneic (at total lung capacity—TLC), all 5-sec frames which were obtained during the breath-holding period can be added together so that an image with better count statistics can be reconstructed.

Another possible source of difficulty in image interpretation is the irregular response of the 11-in.-dia detector of the scintillation camera. Thus a program was included to minimize the effect of these variations. In this operation the frame of data to be "corrected" is augmented on an address-by-address basis according to a computer-normalized frame of data by "flooding" the scintillation camera detector with a sheet source of the same radionuclide used for the organ visualization procedure.

With the computer-controlled system, the viewer is allowed the option of previewing the raw (previously recorded) data in a wide variety of nondestructive formats, and he may choose from these presentations the ones which are to be photographed for final presentation. The form of presentation does not necessarily have to be a facsimile of the original two-dimensional scintigram to be diagnostically helpful. This is particularly true when subtle differences in radionuclide distribution are physiologically significant, yet cannot be readily appreciated on presentations where regional counts are displayed as varying intensities (Fig. 8). For example, the general

distribution of labeled particles from the apex to the base of the lung can usually be better displayed when the location in the lung is plotted in one dimension (e.g. horizontal) against counts accumulated in the vertical dimension. Thus a reversal in the normal relative distribution of labeled particles can be easily recognized on the profile presentation, whereas this subtle reversal may not be readily appreciated on the routine scintigram. Evidence of the reversal of perfusion is important in the evaluation of a number of cardiopulmonary disorders (Fig. 7), even though no well demarcated areas of reduced perfusion are found. Similarly, regional pulmonary ventilation, studied with inhaled inert gases, can be conveniently compared with perfusion studies with this type of display (Fig. 6).

Possibly more important is the ability to obtain numerical values of the counts accumulated in selected regions of interest of the recorded image. While one can usually estimate the relative distribution of radioactivity in various anatomical regions by visual inspection of the conventional scintigram, it is almost impossible to assign an accurate numerical relationship of one area to another. With the digital system, one can obtain reproducible values of regional distribution which can be particularly useful in the followup evaluation of perfusion abnormalities noted on the lung scintigram. Since reperfusion of previously embolized areas often occurs at different rates in different lung regions, a method of numerical comparison is valuable.

In actual practice, we have found that the computer-controlled system is most frequently used in recording "dynamic" studies where time sequential frames of data are recorded in a format for subsequent display and analysis. The operation and results of these techniques will be discussed in other presentations. When the scintillation camera is used for routine "static" imaging, the entire day's work is recorded serially, case by case, on magnetic tape. Each image (frame) is digitally coded with a "tag" word corresponding to the patient's number and view. In this way, the physician can preview each case at the end of the day and photograph the most useful oscilloscope presentations and extract numerical data where appropriate. In many cases, there is no need to preserve the magnetic tape recording following this simple preview technique. However, when a particular study is of potential interest for evaluation later (this might well represent all of our studies eventually), two conventient permanent storage forms are available. Frames of interest can be transferred from the high-speed digital magnetic tape to a tape cassette cartridge containing other similar studies or each frame can be transferred to paper punch tape through the teletypewriter punch unit, to be stored with the patient's record. While this storage format does not adequately substitute for the convenience of the original photographic image, it does preserve the raw data so often required for retrospective studies.

CONCLUSION

Probably the weakest link in gamma-ray scintiphotography is in the method of permanent storage of data. While the original recorded film image may be entirely satisfactory for interpretation in most routine cases, a significant amount of potentially valuable information is often lost and beyond retrieval if one uses direct film storage alone. We have attempted in this paper to describe our experience with one method of digital magnetic tape recording, redisplay and processing of scintillation camera data and to illustrate the clinical value of these techniques.

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