nm/ CONCISE COMMUNICATION

FUNCTIONAL PULMONARY IMAGING

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Analog scintillation camera images of ventilation and perfusion obtained using radioactive particles and gases constitute an effective qualitative means for assessing regional ventilation and perfusion. The activity distribution in these images is distorted, however, by geometric and absorptive differences between areas of lung. In addition, variation in regional image intensity is not restricted to changes in ventilatory gas displacement or perfusion per unit area, but depends on regional lung volume as well. Furthermore, certain important parameters of pulmonary function such as the rate of ventilatory washout, the ratio of ventilation to perfusion, and regional gas exchange are difficult to estimate from sequential scintiphotos. To remove distortion and derive information more directly related to clinically important physiological variables in pulmonary function, we have designed a data processing system consisting of a dedicated general purpose minicomputer and appropriate peripheral devices*. The purpose of this report is to describe functional images obtained with this system which portray the fundamental aspects of pulmonary ventilation and perfusion.

MATERIALS AND METHODS

Patients are positioned for a posterior view before a scintillation camera equipped with a low-energy diverging collimator†. The patient first receives an injection of 10 mCi of ^{133}Xe in saline while breath-holding at functional residual capacity (FRC). Immediately following injection, the patient inspires and breath-holds at total lung capacity (TLC) while the computer system records regional radiation intensity as a single frame in a 64 × 64 matrix. After 10–20 sec of breath-holding, the rate of gas clearance at each matrix point is recorded.

Following the washout of injected ^{133}Xe, the patient inspires a single breath from an anesthesia bag containing 20 mCi of ^{133}Xe. Regional activity is recorded at TLC during a breath-holding interval of 10–20 sec. The patient exhales the ^{133}Xe into a closed circuit spirometer, and rebreathes until an equilibrium (steady-state) concentration is achieved. With xenon uniformly distributed throughout the ventilatory space, the activity distribution is monitored during breath-holding at TLC. Following ventilatory washout, a second single-breath maneuver is performed from the spirometer containing the steady-state concentration of ^{133}Xe. Total lung activity is recorded in order to correct differences in the inspired ^{133}Xe concentrations between the single-breath and steady-state procedures.

Finally, 1–3 mCi of ^{99m}Tc-labeled human albumin microspheres (HAM) is injected intravenously. A single posterior breath-holding frame is collected for use in computing some of the functional parameters, followed by static imaging in four views. In all patients, analog scintiphotos of perfusion and single-breath and steady-state ventilation are obtained. The average time for the routine analog study is ½ hr; only 5–10 min of additional data collection time is required for functional imaging.

DATA PROCESSING AND DISPLAY

Several potentially useful parameters of pulmonary function are listed in Table 1. We have selected the ventilatory efficiency, perfusion efficiency, V/Q ratio, ventilatory clearance, and regional gas exchange for routine acquisition and display as functional images. Each of these indices characterizes a unique aspect of pulmonary function and is determined from X-Y positioning signals of the scintillation camera as described in Fig. 1. Data collected in the

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† Nuclear-Chicago Pho/Gamma HP.

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TABLE 1. EXPRESSIONS OF REGIONAL PULMONARY FUNCTION

Parameter	Definition	Comment
Fractional ventilation (V) or perfusion (Q)	$\frac{\text{Single breath (SB) or Q regional}}{\text{SB total lung}}$	Does not require rebreathing to steady-state (SS), but does not correct for differences in regional geometry, absorption, or lung volume (GAV).
Ventilation or perfusion index	$\frac{\text{SB regional/SS regional}}{\text{SB total lung/SS total lung}}$	Corrects for GAV. Not limited to maximum value of 1.0. Requires rebreathing to SS. Does not reflect regional gas exchange.
Ventilation or perfusion efficiency (V or Q per unit volume of patent air space)	$\frac{\text{SB regional}}{\text{SS regional}} \times f_{conc.}$	Requires factor ($f_{conc.}$) for correcting concentration differences in ^{133}Xe inspired in SB and SS monitoring. Corrects for GAV, and has maximum value of 1.0.
Ratio of ventilation to perfusion	$\frac{V_{eff}}{Q_{eff}}$	Reflects coupling of ventilation to perfusion. Corrects for GAV.
Ventilatory clearance	$\frac{\lambda \text{ regional}}{\lambda \text{ maximum}} \times 100,$ where λ regional is regional rate constant for ^{133}Xe washout and λ maximum is maximum rate of clearance within either lung	Measures ventilation of perfused areas. Not influenced by GAV. May be obtained without patient cooperation.
Regional gas exchange	Q regional $\times$ λ regional	Combines effects of V and Q by expressing bulk gas exchange. With use of radiolabeled microparticles for perfusion, may be obtained without patient cooperation.

central processor are transferred to the disk for temporary storage. Computation and display of a single functional image requires approximately 3 min of operator keyboard interaction. Examples of the results in a normal patient, a patient with recurrent pulmonary thromboembolism, and a patient with pulmonary emphysema of the centrilobular type are presented in Fig. 2.

The ventilatory and perfusion efficiencies express regional ventilation and perfusion per unit volume of patent air space corrected for regional differences in geometry and absorption. The distribution of efficiency levels differs considerably from the distribution of unprocessed digital counts (Fig. 3). Ventilatory clearance, the washout of perfused gas, differs from ventilatory efficiency which is based upon the inspiratory distribution of gas. Since the purpose of respiration is the ordered transfer of gas to and from the blood by the lungs, regional gas exchange is important in assessing the effectiveness of

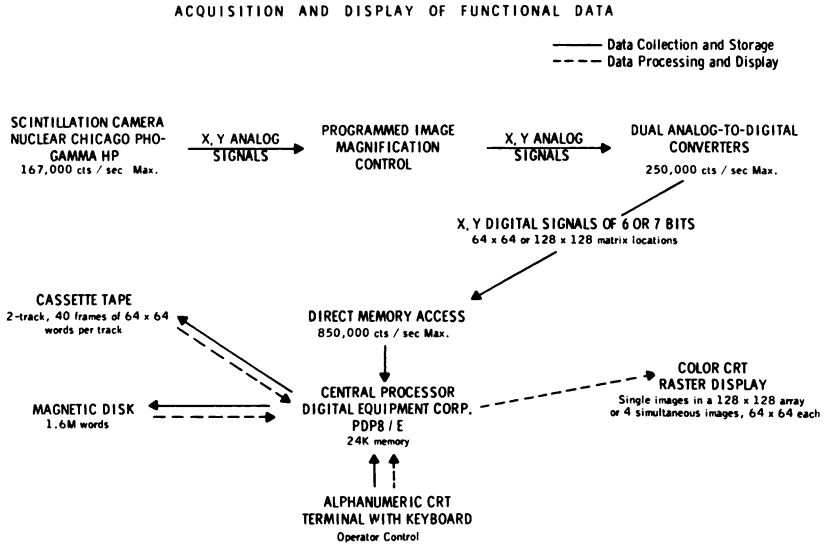


FIG. 1. Acquisition and display of functional data.

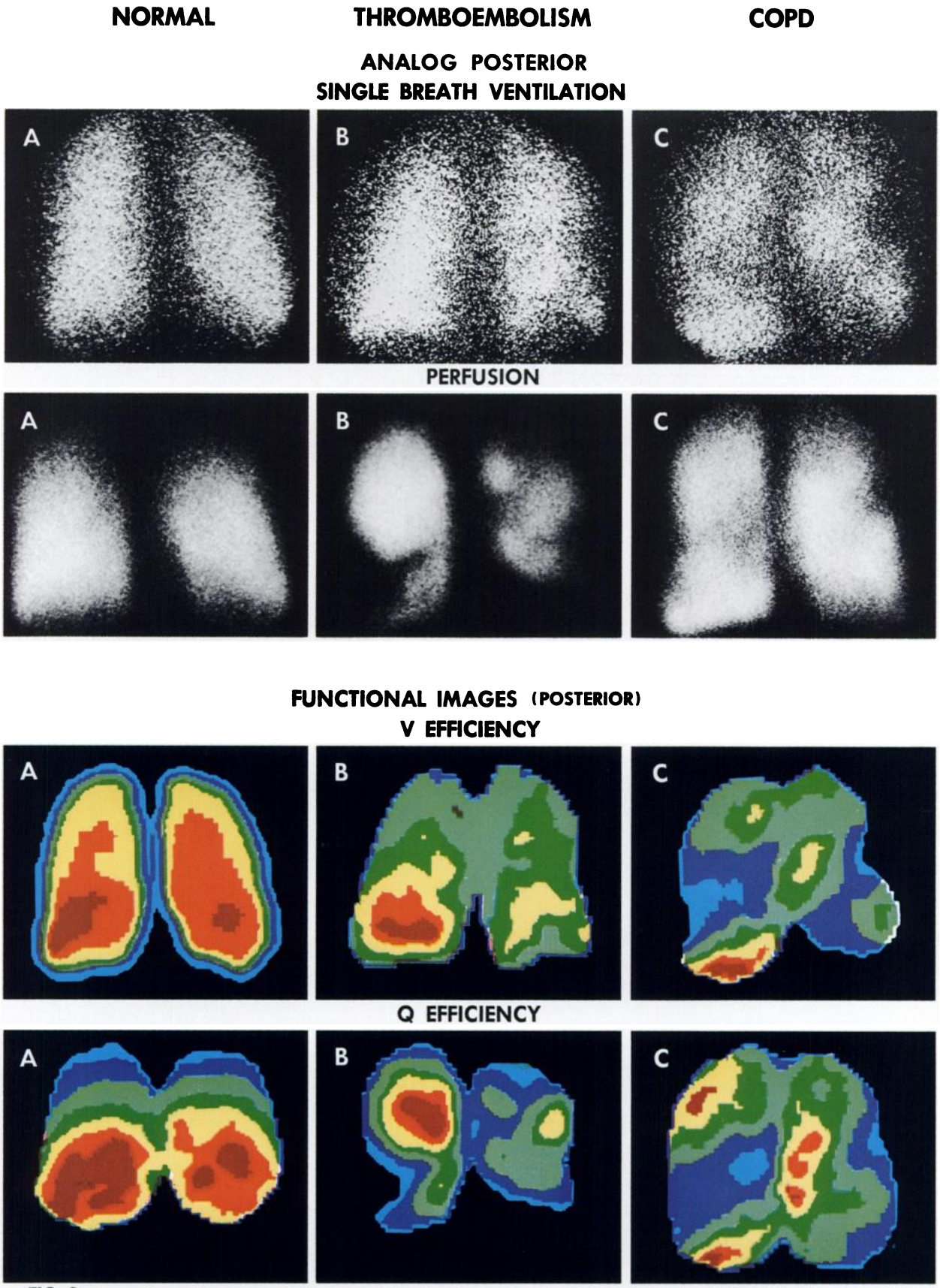
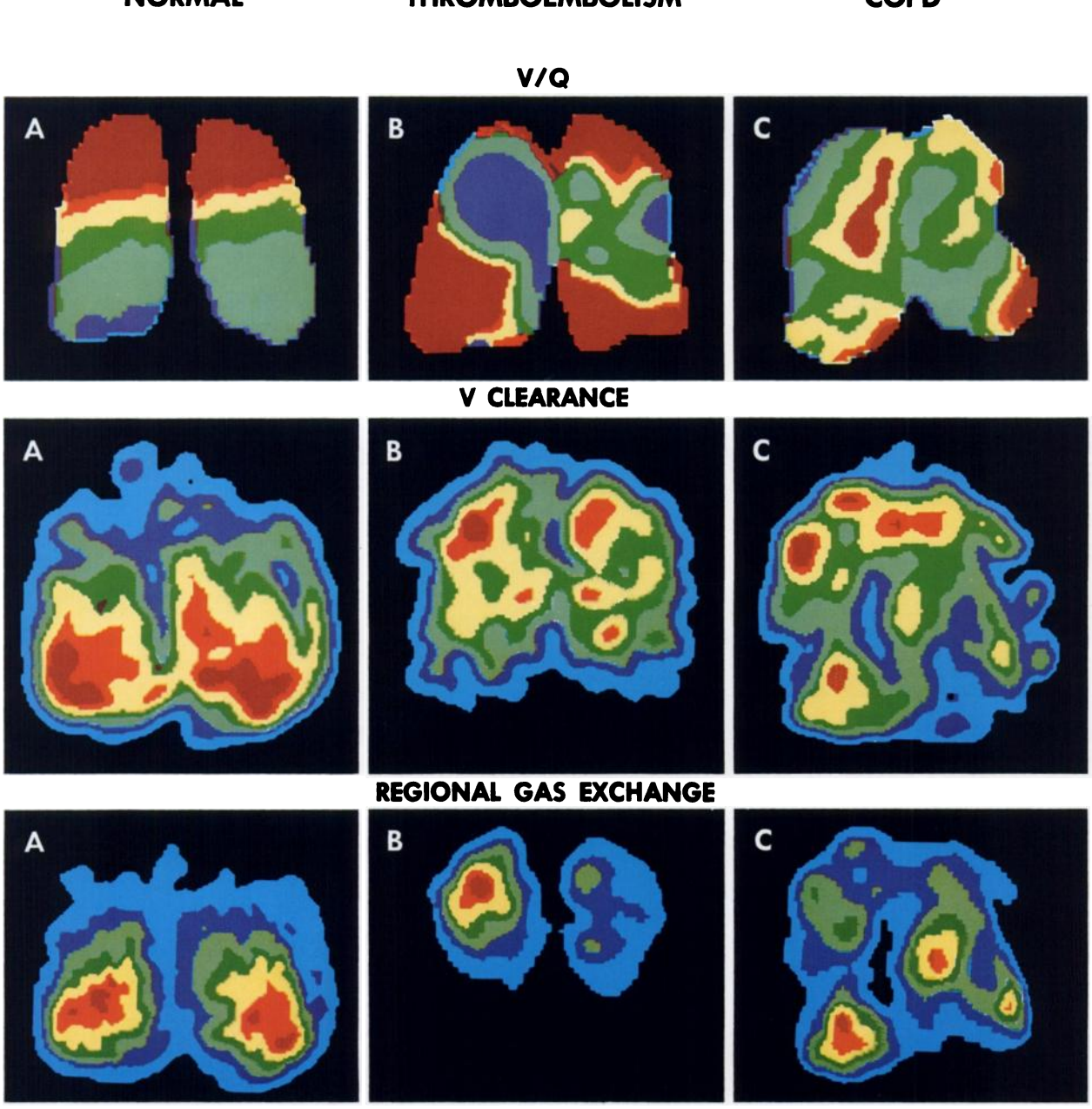


FIG. 2. Comparison of analog scintiphotos and functional images of ventilation (V) and perfusion (Q) in normal patient (A), patient with pulmonary thromboembolism (B), and patient with emphysema of centrilobular type (C). *(Fig. 2 continued next page)*

FIG. 2, Cont'd.



COLOR KEY

V/Q		V or Q EFFICIENCY, V CLEARANCE, REGIONAL GAS EXCHANGE
1.62 Up		86-100%
1.35-1.62		71-86
1.08-1.35		58-71
0.81-1.08		44-58
0.54-0.81		30-44
0.27-0.54		14-30
0 -0.27		0-14

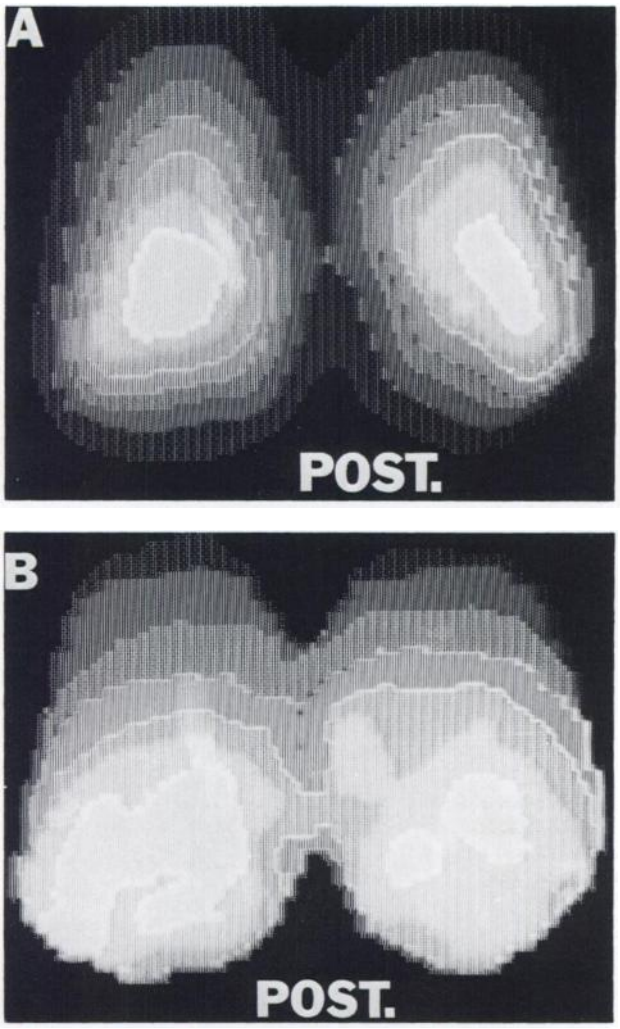


FIG. 3. A, digital image of perfusion. Correction for regional influences of geometry, absorption, and lung volume results in B, functional image of perfusion efficiency. Gray levels were obtained by photographing appropriate sequence of colors on color CRT with black and white film.

respiration. The necessity for patient cooperation creates a problem in testing infants and young children as well as other patients who are too ill to cooperate. Functional images of ventilatory clearance, regional gas exchange, and a modified V/Q ratio can be obtained without cooperation by using the regional rate constants for the clearance of perfused ^{133}Xe and the distribution of perfusion obtained following the injection of labeled microparticles.

Although the CRT display has 64 available colors, statistical limitations of the data probably justify the use of no more than eight colors to differentiate functional levels. Because data collection is limited to short breath-holding and washout intervals, relatively few counts per cell are collected in the 64 × 64 matrix. This reduction in counting rate density diminishes spatial resolution compared to that obtained in the usual static views. Accordingly, data smoothing routines are used to reduce statistical fluctuation. The count at each matrix location is adjusted so that it is within 1 s.d. of the mean of the counts in the adjacent eight locations (statistical bounding). Next, the count at each matrix location is replaced by the average of itself and the eight adjacent locations. In addition, the slope (λ) of the initial portion of the perfused ^{133}Xe clearance is determined by least-squares analysis.

DISCUSSION

Because of inherent functional reserve, a 50–60% reduction in the pulmonary potential for effective gas exchange may occur without producing signs or symptoms associated with respiratory insufficiency. Since non-nuclear pulmonary function studies generally assess the lungs as a single unit, significant disease involving the tracheo-bronchial tree, alveoli, and vascular bed may be present and escape detection. Even when the threshold for clinical awareness has been reached, the regional distribution of physiological derangement cannot be determined by the conventional tests. In addition, the lack of specificity of pulmonary function tests usually prevents one from categorizing the pathologic process as vascular, broncho-alveolar, or a combination of the two. These limitations may exclude valuable information related to the evolution of the physiological changes following the onset of a disease.

Quantitation of regional ventilation and perfusion using a combined single-breath and rebreathing technique with ^{133}Xe was described in 1962 (*1*). Using multiple detectors, the method separated each lung into three or four overlapping regions, and required a determination of total lung volume by helium dilution. Regional ventilation and perfusion were related to an average lung value in a normalized index which could be directly compared from patient to patient. In 1966, the method was modified to eliminate the necessity for measuring total lung volume (*2*). Although this early work advanced the study of pulmonary physiology, several significant limitations were inherent in the methodology. Practical considerations in detector size and supporting electronics prevented monitoring of more than a few areas in each lung and limited spatial resolution. Further degradation of resolution was produced by overlap of the fields of view of the detectors. Also, the ventilation and perfusion indices were normalized to unit lung volume as a means of canceling the effects of geometry, absorption, and regional lung volume, and thus failed to indicate regional gas exchange.

The scintillation camera allows division of the

radiation field over each lung into many discrete areas with much less overlap than the multidetector methods. Several investigators have reported the application of the scintillation camera and digital data processing to pulmonary function studies. Loken, et al (*3*) obtained isointensity contour plots of unprocessed ventilation and perfusion data. MacIntyre, et al (*4*) reported the use of a simulated three-dimensional display for regional ventilatory clearance and gas exchange. In contrast to a two-dimensional display of integers, both of these methods facilitate the visual interpretation of images derived from numerous data points. These investigators used magnetic tape for data collection for subsequent processing at a large computer facility.

The data processing system which we have developed contains a minicomputer despite the availability of larger computers within our institution. General use of quantitative functional images probably will occur only if the necessary instrumentation is economically practical, and is physically located within the nuclear medicine laboratory.

To facilitate the recognition of abnormal patterns, we have used a color CRT to display levels of pulmonary function. A color display rather than a black and white display was selected because of better visual contrast, and the spatial nonlinearity of phosphor response in a black and white CRT. By appropriate arrangement of colors, a suitable gray scale can be obtained for black and white photography as an alternate readout (Fig. 3).

SUMMARY AND CONCLUSIONS

The development of functional pulmonary images which characterize clinically important variables of regional ventilation and perfusion is described. A scintillation camera, dedicated general purpose minicomputer, and appropriate peripheral devices including a color CRT are used for data collection, processing, and display. Functional images from patients with recurrent thromboembolism and chronic obstructive pulmonary disease are compared with those from a normal patient. The routine acquisition of functional information in patients with pulmonary disease should result in earlier diagnoses and lead to improvement in therapeutic approach since a specific response can be quantitated. The capability to follow the evolution of physiological changes in ventilation and perfusion also may provide clues to the pathogenesis of disease.

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