NUMEDICS: A SYSTEM FOR ON-LINE DATA PROCESSING IN NUCLEAR MEDICINE

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A multiterminal system—NUMEDICS—has been developed to study the problems of on-line acquisition, processing, and display of scintigraphic data. The hardware–software configuration of NUMEDICS permits simultaneous and independent operation of terminals in the Division of Nuclear Medicine, the Physics Research Laboratory, and the Cyclotron Laboratory of the Massachusetts General Hospital. This paper describes the hardware and software developments in NUMEDICS which have proven to be of value in clinical and research applications. These features are illustrated by applications to the evaluation of left ventricular performance, three-dimensional imaging, and functional imaging of rCBF.

Nuclear medicine computer systems fulfill three basic functions: data acquisition and storage, data analyses, and data presentation (*1–10*). The purpose of this paper is to report on our experience with a hardware–software configuration—NUMEDICS—which permits simultaneous acquisition, analysis, and display of scintigraphic data from a number of independent sources. NUMEDICS is built around a small general purpose computer (DEC PDP-9) and is totally dedicated to radionuclide studies. It is unique in that it was designed to investigate the problems of on-line data handling rather than for use in conventional nuclear medicine procedures. However, certain features of NUMEDICS that have proven to be of value in actual clinical utilization (*11*) will be presented here. More detailed technical descriptions can be found in *Sharing of Computer Programs and Technology in Nuclear Medicine* (*12–15*).

METHODS

Hardware. The aim of NUMEDICS is to provide rapid and flexible processing of nuclear medicine data from a variety of radioisotope sources within the Massachusetts General Hospital. The system, shown in Fig. 1, has been designed around a Digital Equipment Corporation PDP-9 computer with a magnetic core memory of 16K (K = 1024) 18-bit words and a cycle time of 1 μsec. It is supplemented by a magnetic disk memory (Burroughs B2000) of 10^6 18-bit words, an eight-track display disk (Data Disk Inc. FDP Disk Unit), three DEC tape units, a paper tape reader and punch. Teletypewriter units serve as the means for communication between the terminals and the computer.

Data for the system are obtained primarily from two sources: an Anger camera located in the Nuclear Medicine Division of the Department of Radiology and a multicrystal positron camera located in the Cyclotron Laboratory. Other sources of data include a hybrid positron scanner and various multidetector arrays that are input to the computer through ¼-in. entertainment-quality magnetic tape.

Positional and energy information from the Anger camera is fed into on-site analog-to-digital converters (ADCs) (Searle Radiographics, Model 27851) and transmitted event by event by line drivers over 300 meters of parallel wires to the computer interface circuits. Data are represented as an 18-bit word consisting of eight bits of x and y information, one bit for energy selection and one bit for the transfer command. The interface circuits between the scintillation camera and computer consist of line receivers, a buffer address register, and a buffer data register. The transfer command sends the x, y, and energy data into the address buffer and requests a computer memory cycle through the direct memory access (DMA). During the DMA cycle, the contents of the

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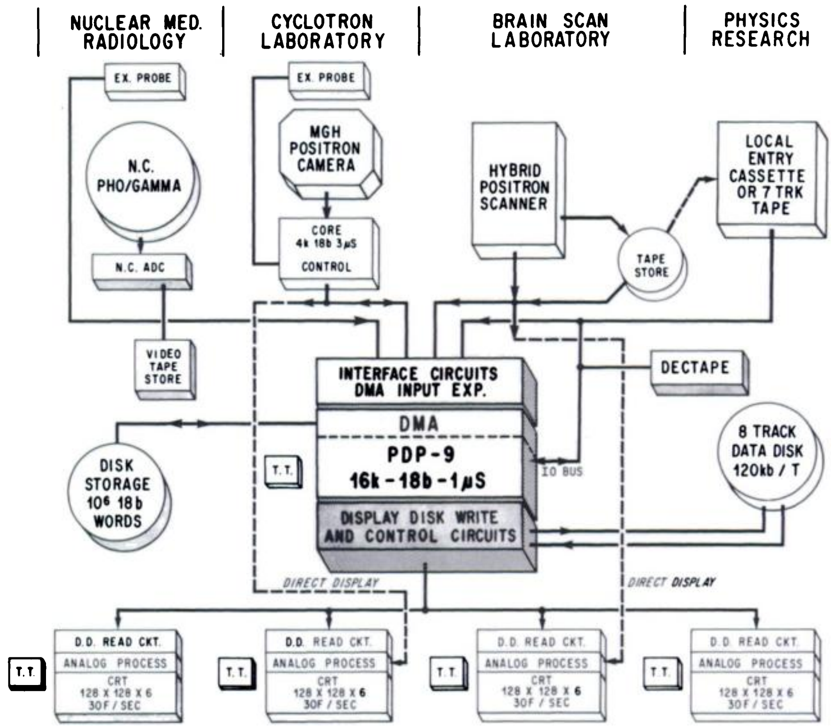

FIG. 1. Schematic diagram of NUMEDICS system showing input devices, processing system, and display devices.

memory location specified by the buffer address register (i.e., the x, y position) are read into the buffer data register, incremented by one, and written back into the core. Following receipt of an (x, y) address, the input to the buffer address register is disabled for 1–2 μsec, a time less than the deadtime of the scintillation camera (Searle Radiographics Pho/Gamma III HP) and ADCs. Events from an external probe are accumulated in a second data register and transferred to core on command.

As previously described, eight-bit x- and y-addresses are available for data storage. In the normal mode, a 64 × 64 × 18-bit image is built up in core by using 12 of the 16 bits to address 4K of core. Two other modes of storage using the same 4K core may be selected. These are the ping pong mode where sequential images can be acquired at a maximum rate of ten frames per second without intervening deadtime and a mode in which two images are acquired simultaneously with data being routed into one or the other by energy selection or by a physiologic trigger. For these cases, two 64 × 64 × 9-bit images are built up in a total of 4K of core.

Coincidence events from the positron camera are accumulated in an external magnetic core memory which is 4K × 18 bits with a 3 μsec cycle time and transferred on command en bloc to the computer in 12 msec. The use of this core memory, which is an integral part of the positron camera, conserves the capacity of NUMEDICS for other tasks during high-speed data acquisition.

The display portion of NUMEDICS is unique. It is built around an eight-track disk display buffer designed for digital recording of video images. The relationship of the display, the computer, and a typical terminal are shown in Fig. 2. This design allows image viewing and analog processing to proceed without interfering with the other functions of NUMEDICS.

In the usual display mode, an image is normalized to a gray scale of 64 levels (six bits of brightness) and stored sequentially on a single-data disk track in a format of 128 × 128 × 6 bits. A set of switches at each terminal permits the selection of any of the

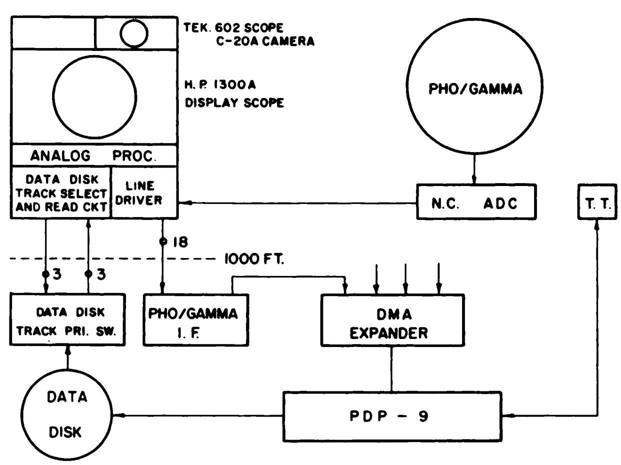

FIG. 2. Schematic diagram of Anger camera terminal and its relationship to computer. Components above dashed line are located at camera 300 meters from computer.

eight tracks. On selection of a particular disk track, the brightness information stored on that track is fed into the analog processor at the terminal and finally to a cathode ray tube (CRT) for viewing. The rotational speed of the data disk sets the image refresh rate on the CRT at 30 cps.

The analog processing circuits at each terminal permit a number of image display variations in real-time and without computer intervention. In addition to the 128 $\times$ 128 brightness mode with 64 gray levels, these include background and foreground subtraction, isometric viewing of the two-dimensional image with rotation, perspective change, tilt and generation of x, y, and isointensity contours.

Software. An expandable operating system, CROSS (*14,15*), (collection and retrieval operating system for scintigrams) has been constructed to permit communication with the computer and to control procedures from the multiple terminals. In order to optimize execution speed and mass storage, CROSS was written in assembly language. Under CROSS, each terminal is effectively independent of the other terminals and has direct control of data collection, analysis, and display. A restriction in the system is that data from the scintillation camera and the positron camera cannot be collected simultaneously.

CROSS has the following functions: (A) the collection of data from the MGH positron camera, an Anger camera, and the hybrid positron scanner; (B) the support of processing systems used both in image manipulation and extraction of dynamic function data; (C) the rapid and easy access to data that have been previously collected or processed; (D) the provision of useful subprograms for file manipulation and system information, and (E) the provision of as much simultaneity as possible within the constraints placed by the available hardware.

Extensive use of a file name and directory structure is used in CROSS to facilitate image storage and retrieval. A four-letter name, date, study, and frame number are associated with all data throughout the system. Frame duration, total counts, and the interframe time are also stored with the images. The identifying information, frame duration, and total counts are automatically displayed with the images. Use of the file name structure permits disk storage to be allocated to users by CROSS and insures that data will not be inadvertently destroyed. In addition, information on system utilization, listing of files resident on disk or DEC tape, file deletion, and file transfer are all made possible by adopting a directory structure.

Of the 16K available memory locations, 3K are reserved for the resident root, 1K for overlay pages, 4K for data storage, and 8K for data processing. The computer's interrupt structure is used so that simultaneous operation of input/output devices becomes feasible. Data acquisition with either the Anger or positron camera may proceed while previously stored data are being analyzed and displayed.

A particularly valuable feature of CROSS permits the user to create, store, and recall complicated data acquisition procedures. The number of frames, their duration, and the interframe times can be specified by the user. The duration of each can also be controlled manually at the teletype or by specifying the total number of counts required. A simple example of a collection procedure used for radionuclide angiography of the brain is shown here (> indicates user response):

```
CODENAME =
> FLOW
MAX NO. OF FRAMES =
> 20
CODES =
> F1-19 T2.0
> F20 C300
> W1-19 T0.0
```

This code specifies that 19 images are to be acquired for a duration of 2 sec each. The 20th frame is automatically terminated when 300K counts have been received. The procedure library is stored on the disk so that the user need only specify the procedure name when he wishes to acquire data under that protocol. There is no restriction on the number or combination of different frame and interframe times. In addition, the frame times and interframe times (W) are stored with the data for use in subsequent mathematical analyses.

To facilitate clinical applications and provide flexibility in a research environment where the optimum processing procedure often cannot be predicted, two processing executives SPS (scintigram processing system) and DPS (dynamic processing system) were developed (*15*). The executives control the sequencing of routines, input of parameters, and the handling of input and output files.

Each processing routine is modular and performs a single function. The SPS and DPS executives allow the user to specify any combination of 70 routines now in existence so that a new and complex processing procedure often requires only a different sequence of routines rather than new programs or the rewriting of old programs. To minimize a clinician's interaction with the computer, the input files, routine sequence, and any variables required by the routines once assigned are "remembered" by the executives until changed or deleted. Furthermore, any variable necessary within a routine but not as-

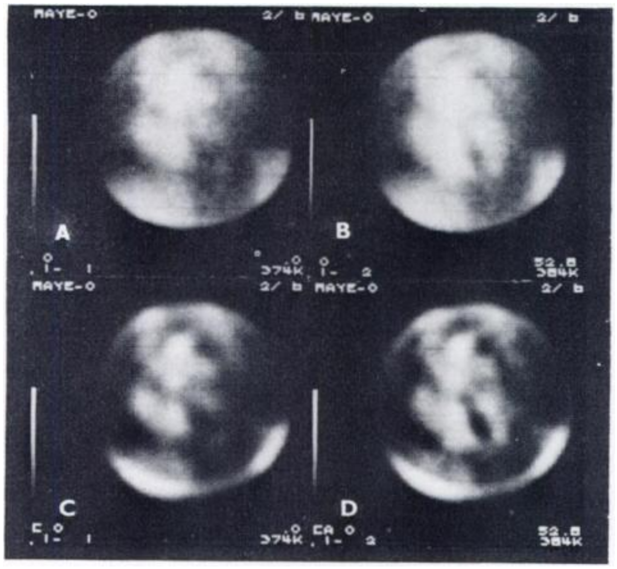

FIG. 3. Cardiac images obtained during end-systole (left) and end-diastole (right) in LAO projection. Standard display mode (A and B) is shown and same data after processing with fixed filter (C and D) are given. Note clear visualization of left ventricle, left atrium, right ventricle, right atrium, intraventricular septum, and aorta.

signed by the user is automatically set to a standard value. The user can therefore carry out a standard processing protocol or vary the parameters in a new procedure with a minimum number of specifications.

APPLICATIONS

NUMEDICS went into full operation in 1972. The system is used by investigators in the Physics Research Laboratory, Pulmonary Laboratory, Anesthesia Research, Department of Radiology, Cardiovascular Research, Neurosurgical Service, and by nuclear medicine technologists. NUMEDICS has played an important role in a wide variety of studies including image enhancement (*16,17*), three-dimensional reconstruction (*18*), functional imaging of rCBF (*11*), analysis of pulmonary function with positron-emitting gases (*19*), imaging of the myocardium with ^{13}N-ammonia (*20*), and a number of more routine clinical applications (*11*).

The flexibility and capacity of a system such as this is best appreciated by reviewing the results of a few applications. Only a synopsis of the data-handling techniques will be given here. More detailed reports have been presented elsewhere (*21–23*).

Evaluation of left ventricular function. Figure 3A and B show images obtained during end-systole and end-diastole by synchronizing (Brattle Instruments Corp.) a scintillation camera and the patient's electrocardiogram. In this study, ^{99m}Tc-albumin was the tracer and the patient was viewed in the left anterior oblique projection. Both the end-systolic and end-diastolic images were obtained simultaneously by double buffering the data as two 64 × 64 × 9-bit images in 4K of core.

This study is initiated and controlled from the terminal in the Division of Nuclear Medicine. Once the identifying information has been entered, the user need only request data acquisition under the appropriate data acquisition protocol stored on the disk. At the end of the data acquisition phase NUMEDICS automatically provides a display of the resulting images. Further processing can be requested as in Fig. 3C and D to sharpen the cardiac borders. The quality of these images permits calculation of the left ventricular injection fraction (*24*) and visualization of the major cardiac structures: left ventricle, right ventricle, right atrium, left atrium, interventricular system, aorta, and pulmonary outflow tract. Finally, the detection of ventricular wall-motion abnormalities may be facilitated by cyclically presenting the gated scintigrams on the CRT display to give an impression of the beating heart (*21*).

Three-dimensional reconstruction. An interesting and important use of the computer system is in determining the three-dimensional distribution of activity within a patient from a series of scintigrams taken at uniformly spaced angles around the patient (*18*). The computed three-dimensional activity distribution is displayed as a sequence of two-dimensional images of the activity on different transverse sections through the patient. Figure 4 illustrates some of the results of a three-dimensional study of a dog's lung (*22*). The posterior views of the dog's lung before (Fig. 4C) and after (Fig. 4D) the creation of an

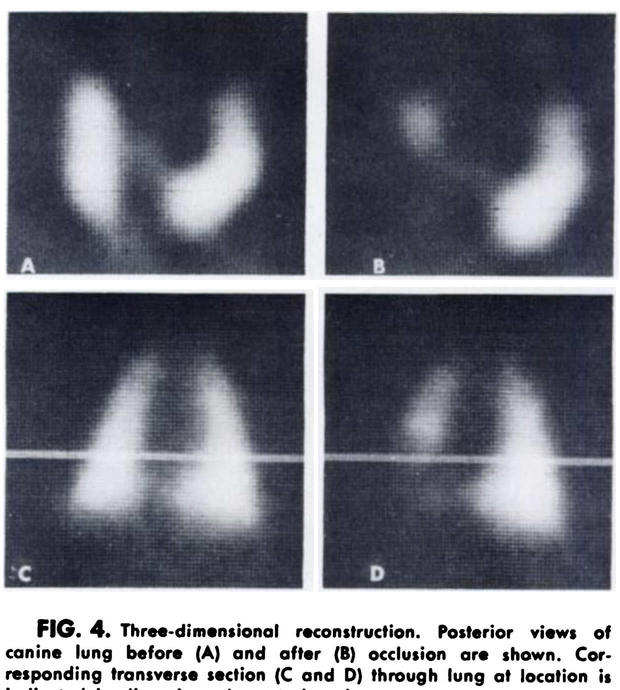

FIG. 4. Three-dimensional reconstruction. Posterior views of canine lung before (A) and after (B) occlusion are shown. Corresponding transverse section (C and D) through lung at location is indicated by line through posterior view.

FIG. 5. Functional image of rCBF in left hemisphere of normal human brain as measured with ^{133}Xe and Anger camera. Brightness at each point in image is proportional to ratio of moments $\Sigma_i N_i / \Sigma_i t_i N_i$, where N_i is number of counts received between t_i and t_{i+1}.

occlusion in the left lower portion of the lung are shown. Corresponding computed images (Fig. 4A and B) of activity on a transverse section through the lungs are also shown. The location of the transverse section is indicated by the bright line in the posterior views. For this lung study, albumin microspheres labeled with 1 mCi of ^{68}Ga, a positron emitter, were used. With the MGH positron camera 23 emission images were taken at uniformly spaced angles around the dog. In addition, with a plane source of activity a corresponding set of 23 transmission images through the dog were collected and used to correct the emission images for the effects of absorption (*18*). The data were collected and processed under the CROSS operating system. The collection time for a set of 23 images was 23 min and the processing time for each transverse section was 1 min.

Functional imaging of rCBF. A number of investigators have used the scintillation camera and ^{133}Xe to measure rCBF. Our technique is similar in most respects except that the catheter is placed in the internal carotid artery by the femoral route and we usually employ a vertex projection. The major differences are in the data processing and presentation. Here NUMEDICS plays an essential role. Acquisition of data over a 20-min period is initiated at the terminal in nuclear medicine and sequential images with durations ranging from 0.5 to 50 sec are obtained. As usual, the sequential images are digitized on a 64×64 raster. Each of the 4,096 image cells are treated as though they correspond to the output of an independent probe. The washout rate is computed for each image cell resulting in a matrix of 4,096 flow values. These results are then presented as an image with the intensity proportional to flow, i.e., a "parametric" or functional image (*25*).

Processing can also be initiated and controlled from the acquisition terminal. Various models can be applied to analyze the data (*23*) including initial slope, height over area, and ratio of moments. Figure 5 shows a functional image of rCBF in the left hemisphere obtained with a vertex projection and the ratio of moments (*23*). Only a few minutes are required to manipulate the sequential images after the study and obtain this type of display (the numerical calculations take about 1 min).

DISCUSSION

NUMEDICS was begun in 1970 at the Physics Research Laboratory of the Massachusetts General Hospital. It was the first nuclear medicine computer system to employ both multiprogramming concepts and a small computer to serve multiple users simultaneously. The system concept was originated by Brownell, Burnham, Pizer, et al (*12*). Approximately 3 man-years were required to design and program the operating system—CROSS—and the SPS and DPS processors described above.

In NUMEDICS the computer memory is limited to 16,000 18-bit words but as with other disk-operating systems, the memory is effectively expanded by the ease of information transmission between computer core memory and disk. Thus, another one million words of memory are available to NUMEDICS for storage of programs, unprocessed scintigrams, and processed data. Storage or retrieval of information typically requires about 60 msec with the present disk unit whereas access times for magnetic tape can be as much as several minutes. Programs are swapped into and out of core under the control of the disk-operating system CROSS. Only the program or segment of a program currently being executed need be in core at any time. Multiprogramming essentially doubles the throughput of NUMEDICS as compared with systems with single task designs.

Storage of incoming scintigraphic data represents the highest priority task. However, since these data enter the computer on a cycle-stealing basis, the computer can perform other tasks as long as each frame can be stored at the appropriate time and new programs can be accessed as desired. This multiprogramming capability is made efficient in NUMEDICS by utilizing a disk with one head per track (i.e., a fixed head disk). Similar performance can be obtained by using multiple moving head disks. In that case, one disk is usually reserved for programs and processed data and another for storing incoming data.

It is interesting to compare CROSS with more general multiprogramming operating systems used in nuclear medicine. CROSS represents an operating system developed specifically for nuclear medicine computer applications. The nucleus of CROSS occupies only 4,000 memory locations with all additional memory available for applications. In addition, CROSS is optimized with respect to execution speed within the constraints of its hardware environment. Recently, general multiprogramming operating systems developed by the computer manufacturers have been modified for use in nuclear medicine computer systems (*26*). This approach reduces the necessity for the development of device handlers, system supervisors, and system monitors while permitting software development to proceed as one of the simultaneous tasks. On the other hand much more core is required, the system software is not optimized for nuclear medicine applications, and the increased execution time required by the general multiprogramming operating system may be unacceptable for some applications.

We have already described the use of the independent disk buffer for providing image display and analog processing at the multiple terminals without computer intervention. The disk-driven 128 × 128 raster display with 64 gray levels has had wide acceptance among the users of NUMEDICS. Although scintigraphic data is acquired on a 64 × 64 grid, the use of an interpolated 128 × 128 display format yields significant improvement of the observer's image perception (*17*). A comparison of a 64 × 64 display and 128 × 128 interpolated display is shown in Fig. 6. Although it is true that no additional information is present in the interpolated display, the disturbing artifacts produced by the coarser 64 × 64 raster are reduced, thereby improving observer confidence and performance. This result cannot be obtained by a simple smoothing or blurring of the image on a 64 × 64 raster.

The major contributions from the development of NUMEDICS are in three areas: first, NUMEDICS has shown the power of a small computer with a disk-operating system for simultaneously providing a multiuser, multitask scintigraphic data-processing facility; second, the development of a high quality disk-driven display system; and third, the extensive use of a file structure to provide patient identification information, to pass parameters to processing routines, and to automatically allocate disk storage.

A number of valuable nuclear medicine procedures that depend on the computer have been identified. Computer systems are no longer confined solely to the research laboratory and the large medical center but are appearing in smaller nuclear medicine laboratories, community hospitals, and even private clinics. We have seen the first generation of commercial data-processing systems evolve from rather crude beginnings with magnetic tape as the primary

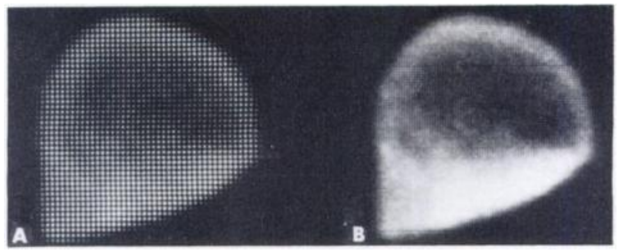

FIG. 6. Comparison of same brain scintigram in two display modes—interpolated 128 × 128 (A) and 64 × 64 (B).

medium for data and program storage to the current systems based on the moving head disk. Now a new trend is emerging in nuclear medicine computer systems employing multiprogramming concepts similar to those developed in NUMEDICS.

Simultaneous data acquisition and processing from multiple imaging devices clearly represent technologic advance and sophistication. However, careful consideration must be given to the integration of data processing in functioning nuclear medicine clinics. Data acquisition has been simplified to the extent that technicians can perform this task along with their other duties. Data processing, on the other hand, is often time-consuming and interactive. Because of this, our experience suggests this task is best left to specially trained technicians working under the supervision of the nuclear medicine physician.

There is still a need, however, for systems designed so that work can be completed rapidly without interfering with normal work patterns in the clinic. A multiterminal, multitask approach that permits the physical separation of data acquisition, data processing, and analysis offers a practical solution for clinical application.

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