Teaching Editorial

Nuclear Medicine Computer Systems—Hardware

The computer, which began its life in nuclear medicine as a toy for rich laboratories, has become an integral and basic part of nuclear medicine procedures. The current practice of nuclear medicine would be impossible without the power of the modern computer system. The evolution of the computer has not only produced very powerful and versatile systems but it is also responsible for significant changes in camera design, so that the modern camera has begun to resemble an "imaging computer." This article and a second on software (JNMT, September 1985) will review some of these advances in computer systems. The discussions are aimed at the practicing technologist who has a basic understanding of computer applications in nuclear medicine, and do not provide a comprehensive review of computer techniques and applications.

The logical design of the nuclear medicine computer system as represented in figure 1 has remained virtually unchanged throughout its evolution. There have, however, been a number of changes in the methods by which the various parts are implemented and the scale on which they exist in modern systems. In some instances, there is considerable overlap in the function of the various parts. This article will deal first with the individual components illustrated in figure 1 and then present a short overview of some existing specialized system configurations.

CENTRAL PROCESSING UNIT

The central processing unit (CPU) is the part of the computer that controls all of the operations of the system. It is the master controller and the arbitrator of conflicts concerning allocation of resources. It decides which of the peripherals will be serviced and what instructions will be executed. Although purists would argue that neither memory nor the arithmetic logic unit (ALU), which does the actual computing, are part of the CPU, most reasonable people can lump them together with little difficulty. From the user's standpoint, the design of the CPU and the ALU have not changed noticeably over the years. The primary advances have been in the form of increased calculation speed and significantly smaller physical size. In some systems, a larger word size also enhances the system's capacity.

The array processor, discussed in detail below, has significantly increased the calculation speed for complex operations such as image filtering for resolution recovery and tomographic image reconstruction for single photon emission computed tomography (SPECT). The centralized design, in which a single CPU is the ultimate ruler of the system, has been replaced in some systems by a number of smart controllers that arbitrate the operation of the system through a set of predefined rules governing priorities and timing. The smarter peripheral controllers are often individual computer systems in themselves that treat the rest of the system as a mere peripheral. A configuration results which, in reality, is no longer a single system but rather a collection of systems talking to each other in a way that previously had been reserved for networks of larger computers.

MEMORY

Memories are described both by their physical implementation and by their logical construction. Logically, memories can be divided into at least two categories: Read-only memories (ROMs), whose contents can only be read; and read/write memories, whose contents can be altered by the user. ROMs are commonly used for storing programs that are used repeatedly and are not changed, either by their use or by further development. One example is the program that

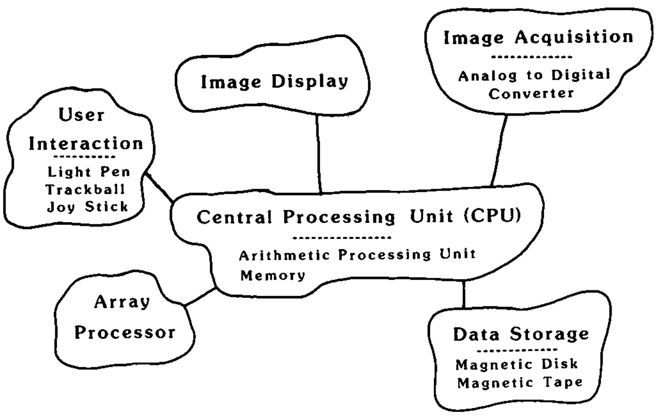

FIG. 1. The nuclear medicine computer system is comprised of a number of logical subunits.

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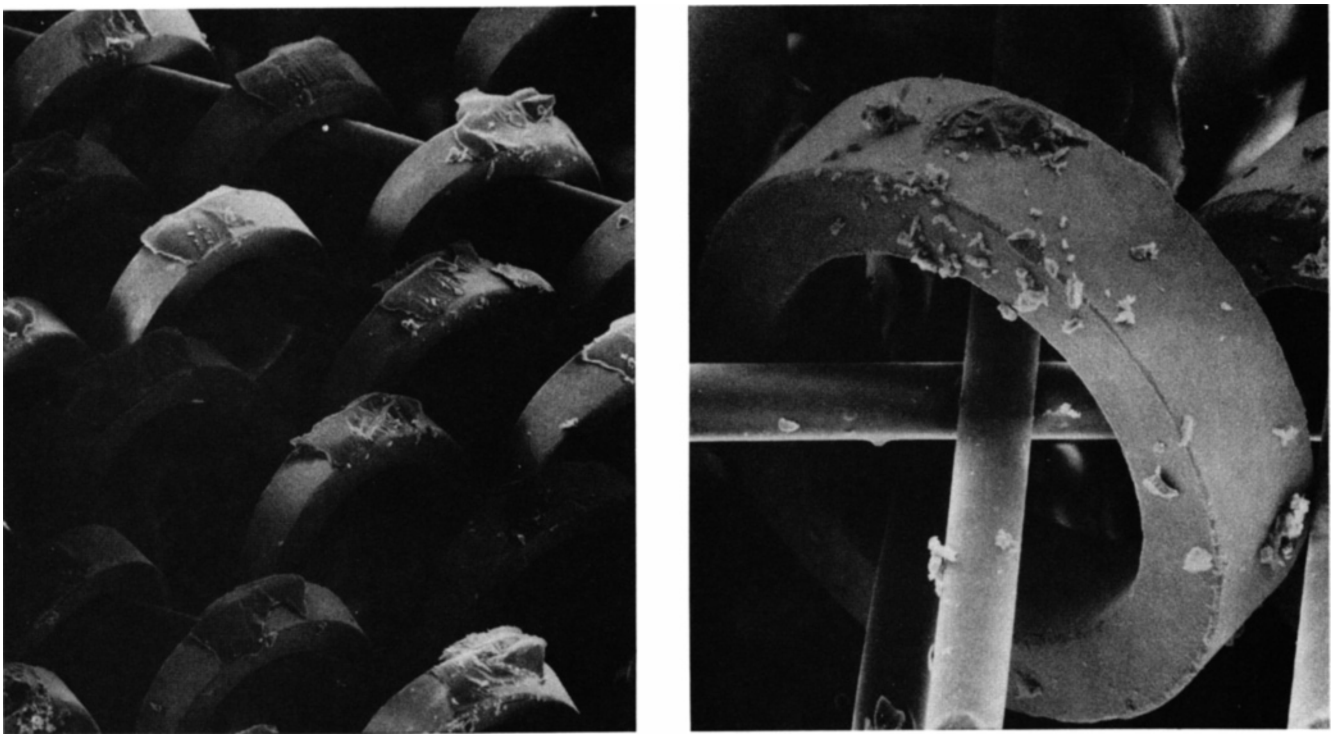

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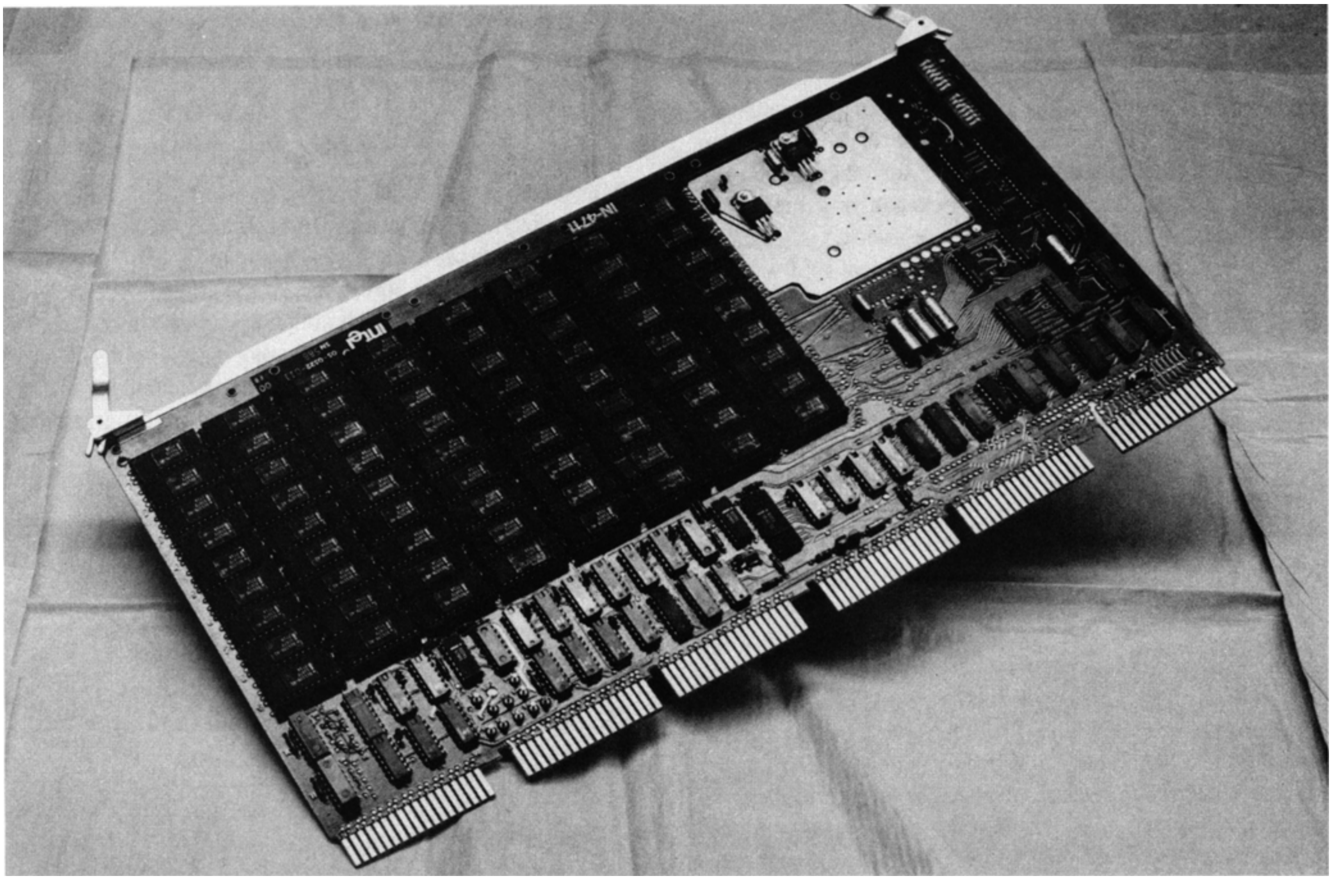

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FIG. 2. A) An electron micrograph of a ferromagnetic core memory element. B) A 32k-word solid-state memory board from a modern computer (*1*).

brings the computer to life when it is turned on. This "bootstrap" program is available without any access to disk or input from the user and is unchanged by its execution. Read/write memory is used to store data or programs temporarily. Applications for this memory are found in the main part of the computer and in the parts of the scintillation camera's uniformity correction devices that store the correction factors treated by periodic calibrations.

Computer systems are often discussed in terms of the number of memory locations and the number of bits per word, or word size. The number of bits in each memory location will usually determine the number of counts that can be stored in each picture element of the image collected from the scintillation camera. However, the count/pixel capability of any particular system is also a function of the image acquisition hardware and software. At least one system is sold that uses a 16-bit computer memory, but is limited to 10 bits/pixel in clinical images, which imposes an upper limit of 1,024 counts/pixel.

The word size of the computer may also determine the number of memory address locations that can be addressed directly. A 16-bit word can address 65,536 locations. If more locations are used, then secondary address registers, or extended memory control registers, must be provided.

The number of memory locations will determine the amount of clinical data and programs that can be held in the memory at one time. Space must be provided in the memory at all times for the software that controls the computer so that one can never completely fill the memory with clinical data. Early computer systems had as few as 4,096 words of memory, with additional memory costing many thousands of dollars. Currently, it is not unusual to find as many as 512,000 to 2 million words of memory in a computer. This increase has been made possible by the significant miniturization of electronics.

One of the early computers used in nuclear medicine, the Digital Equipment PDP-9, was designed for a maximum of 32,768 words and used magnetic core memory (Fig. 2); today it is seldom found except in some very specialized computer systems. Even if this computer had been technically capable of supporting the memory, it would have required 133 sq ft of floor space to house the cabinets for 1 million words of memory. The same amount of memory today can be housed on one or two printed circuit boards (Fig. 2). Although this may seem like a large amount, it must be remembered that a gated cardiac acquisition consisting of 32 128 $\times$ 128 images requires 512,000 memory locations. The creation of multiuser systems has also increased the need for large memories.

IMAGE ACQUISITION

The analog image information produced by the scintillation camera normally consists of three signals: the X and Y signals representing the position of the photon interaction in the crystal; and the "unblank" pulse indicating that a given interaction deposited an amount of energy in the detector equal to that of the photon energy of interest. In some systems, a signal, Z, representing the energy of the photon, is also provided so that complete energy spectra as well as images can be collected from the camera. In systems in which the camera is an "all-digital" camera, the image data may be transferred to the computer through a direct digital interface. This eliminates many of the problems of the analog circuitry, but restricts the potential buyer because the digital data transfer mechanisms are normally proprietary and the problems of bridging between systems from two manufacturers are usually more of a task than the ordinary clinical user is willing to tackle.

ANALOG TO DIGITAL CONVERSION

Because the computer is a digital system, it cannot directly use the analog position signals produced by the camera. The X and Y position signals must be converted to digital values to be processed by the computer. A number of analog-to-digital converter (ADC) designs have been previously used in nuclear medicine systems. Currently, the most common type of ADC is the successive approximation converter (Fig. 3). This device, which operates by a method that has been compared to weighing material on a laboratory balance, makes sequential guesses or approximations to the analog value. Starting with the bit representing the largest power of two, the converter sets the bit and then converts the digital number back to an analog signal through a digital-to-analog converter (DAC). The analog signal is compared to the incoming signal. If the test value is too large, the bit is turned off. If the test value is smaller than the incoming signal, the bit is left on. The ADC steps through each of the bits in the digital word and performs this process each time. If an 8-bit digital word (0–255 position values) is used, the conversion will take eight cycles. This converter is fast and, with relatively conventional electronic designs, conversion times on the order of 1.5 μsec or less can be easily obtained.

Although the ADC known as a "flash" converter is not used for digitization of the camera image by the image collection system, it is worth mentioning because it is found in some "digital cameras." The flash converter is a single integrated circuit that contains the equivalent of a large number of single channel analyzers (SCAs). The analog signal is presented to the input of the chip and simultaneously tested by each of the integrated SCAs. The output of the array of analyzers is coded into a single digital word and presented to the output lines of the circuit. Because this technique requires no iteration or sequencing of the conversion process, it is essentially a realtime operation and provides virtually instantaneous analog-to-digital conversion. Integrated circuits capable of conversion of analog signals to 6-bit digital values in 10 nsec are available for less than $100. This circuit was initially designed by the electronics industry for realtime digitizing of high speed signals such as television images. The specific design details of the various "all-digital" cameras are proprietary, but the digitization of the photomultiplier signals in the detector is accomplished by the use of flash converters.

The short conversion time of less than 1.5 μsec for the suc-

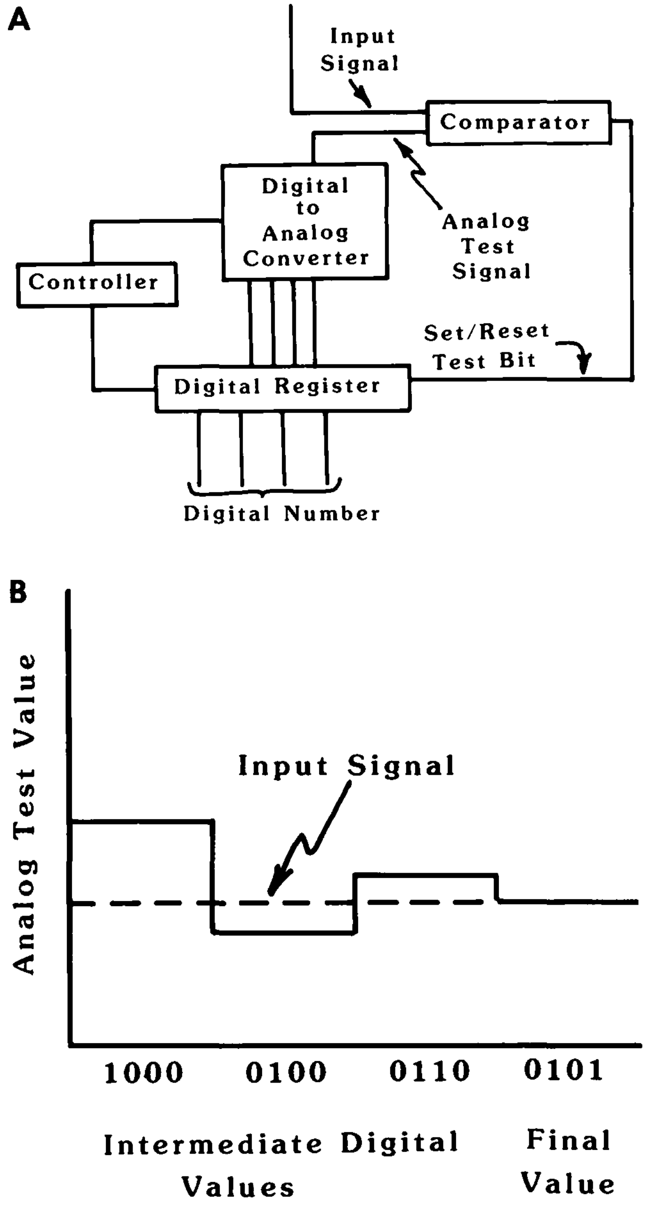

FIG. 3. A) The successive approximation analog-to-digital converter is the type most commonly found in current nuclear medicine computers. B) The conversion is accomplished by comparing a generated analog signal to the incoming position signal. The analog signal is generated by clearing or setting sequentially lower bits in the digital word.

cessive approximation converter can contribute to count loss in collection of data from the modern high speed cameras with count rate capabilities of upwards of 200,000 counts per second. Although data can be transferred from the output of the ADC to the computer memory without the intervention of software, the input/output data buss of the computer can only perform one data transfer at a time. If data are being passed between memory and display or memory and disk, the transfer from ADC to memory may have to be delayed for several microseconds. This delay, in turn, would prevent the ADC from processing a new event. To counteract the effect of these delays, most systems have temporary storage buffers built into both the analog and the digital sides of the ADC. These first-in, first-out (FIFO) buffers tend to derandomize the events from the scintillation camera and cut down the losses due to processing dead time.

EXTERNAL DATA STORAGE

External storage is an important part of the computer system. It is used for data storage, software storage, and transferral of clinical data between computer systems. Magnetic disk storage, found on all clinical computers, is the primary operating medium from which the system loads programs and writes patient data for later retrieval, analysis, and display. Magnetic tape, although found on many systems, is not universally compatible, and is primarily a medium used in research and other systems in which clinical studies must be archived for extended periods of time. Cartridge tapes or high speed streaming tape systems represent low-cost archival storage alternatives to disks.

Changes in magnetic storage media have occurred more in the form of decreased size and increased capacity rather than in basic design. Early hard disk systems had storage capacities of 128k to 1 million words of storage, whereas floppy disks had even less. Present hard disk storage capabilities range from 40 to 300 million bytes.

The Winchester disk is a sealed, nonremovable unit which incorporates both sophisticated recording techniques for error detection and correction and high precision positioning mechanics. The mechanical construction provides for positive head retraction and a resting place for the read/write heads when electrical power is removed. These two aspects make the Winchester drive particularly suitable for portable data collection systems.

The cost of disk storage technology did not drop as rapidly as that of memory because of the large number of mechanical components required for high density storage. The introduction of the Winchester technology, however, has recently provided a significant increase in the amount of storage capability for dollar investment in hardware. Current disk systems have storage capacities of 40 megabytes in hardware configurations approximately the size of an 8-in floppy disk drive, and range from $5,000–$10,000.

The amount of disk storage required by modern nuclear medicine systems can be appreciated by considering SPECT. A data collection consisting of 128 × 128 8-bit images collected at 128 rotational positions produces over 2 million bytes of data. If tomographic slices are created for each of the 128 lines in the raw data matrix, another 2 million bytes of data are created. If more acquisitions are necessary to image the entire organ, then the storage requirements increase correspondingly. For at least one clinical application, 40 megabytes of data storage capacity could be justified with ease.

The optical disk, as a result of its use in other areas of medical information, is a storage technology currently available to nuclear medicine. Differing from magnetic storage media, optical disk storage consists of a thin metallic film mounted between two plastic or glass plates. Data are stored on the disk by a laser that burns a series of holes in the metallic film. Once it is implemented, the optical disk is a very attractive option because it provides relatively inexpensive archival storage for clinical studies. Furthermore, the data storage is quite literally "done with mirrors" so that the system does not require the very close physical tolerances found in magnetic disk systems; it is very stable and free from the usual sensitivities to dirt and dust in the environment. The one significant disadvantage of the optical disk is that the media is not reusable. Once data are recorded on the disk, they are permanent.

ARRAY PROCESSORS

The complexity of modern nuclear cardiology procedures and SPECT have produced a need for high-speed computation capabilities. Array processors are appearing in nuclear medicine computer systems in response to this need. They are special purpose computers designed solely for the purpose of performing repetitive calculations on large numbers of data values.

The basic construction of an array processor is shown in figure 4. The interface to the host computer is used to transfer both raw and unprocessed data to the array processor and the processed data back to the main computer. The interface is used to transfer instructions to the array processor. The array processor generally has its own memory, which eliminates the need to interrupt the main computer each time it requires new data or has data to store. Therefore, the array processor can operate faster because the memory can be optimized for very fast sequential operations. It also lets the main computer proceed with sequential operations while data are being processed. Although there are many array processor designs, one method for attaining the desired high processing speed is the use of "pipeline processing." In the general purpose computer, the processing of any data must proceed in a stepwise fashion with each calculation being performed and completed before the next can start. The normalization of an image point for display by subtraction and normalizing the remainder to a maximum value of 100 as produced by the equation:

$$\text{NEW VALUE} = 100 \times \frac{(\text{VALUE - BACKGROUND})}{\text{MAXIMUM}}$$

requires three arithmetic steps, each of which must be completed before the next can begin. Because the computer generally cannot look ahead to determine what will be done with the intermediate results, data must be placed back in temporary memory locations and retrieved before further steps are taken. In addition, each intermediate step and image point must be completed before the next. This stepwise data manipulation places a very firm upper limit on the speed with which results can be calculated.

The pipeline processing method places several arithmetic processing units (APUs) into series so that intermediate results are passed directly from the first to second, the second to the third, and so forth (Fig. 4). The APUs are connected together in such a way that they can all process data simultaneously. While the second APU is performing a multiplication on the first image point, the first APU can perform the subtraction of background on the second point, and so forth down the line of processing units so that a number of image points may be in the pipeline and processed at any given time. It is impossible to give specific values for the amount by which calculation times can be reduced using the array processor, but factors of 10 to 20 are not uncommon. Therefore, a calculation that previously required 20-min processing could possibly be done in only 1 min. This is a very important consideration

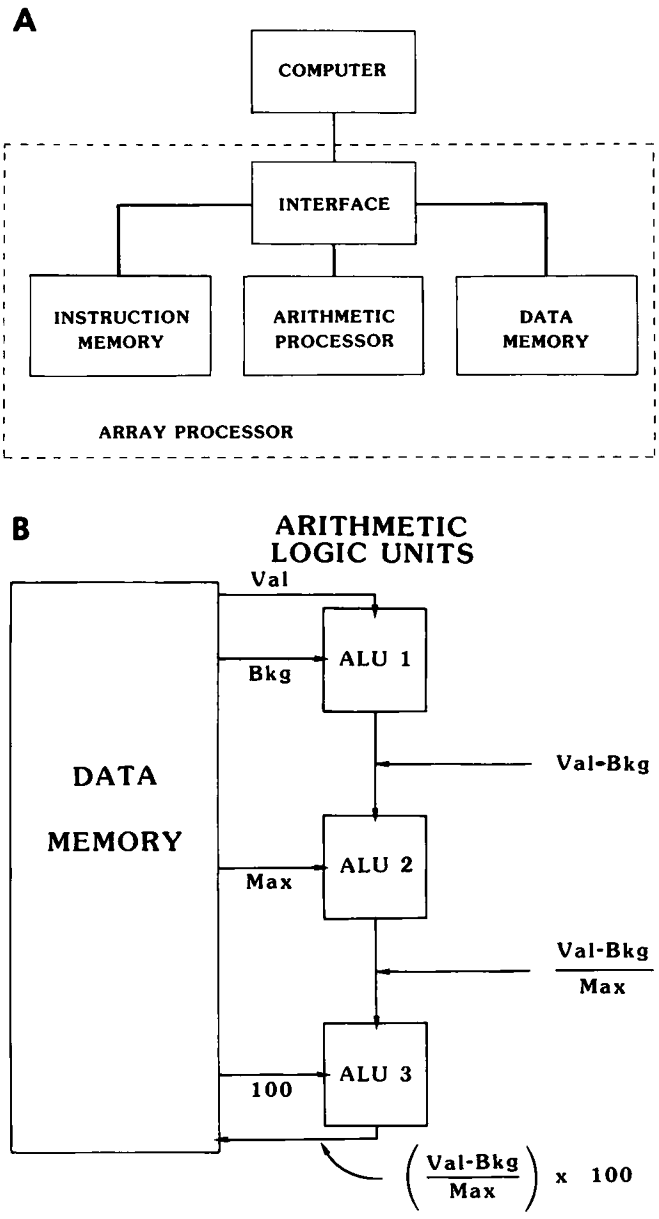

FIG. 4. The array processor is a special purpose computer designed for repetitive calculations on large numbers of image points. B) The pipeline processor provides high speed calculation capability by enabling the simultaneous operation of a number of serially connected arithmetic units.

because many current diagnostic procedures (e.g., phase and amplitude analysis of cardiology studies or SPECT reconstruction) require a large amount of image processing. Prices for an array processor range from $5,000 for a relatively simple system to more than $30,000 for more complex and powerful systems.

DISPLAY

Although computerized clinical studies are performed with the primary aim of producing quantitative indicators of patient health, the practice of nuclear medicine remains principally an image-oriented discipline. For this reason, the image display is one of the most important parts of the computer system. Its basic design is shown in figure 5. The image to be displayed is transferred from the main memory of the computer to the memory of the display unit. The data from which the displayed image is generated is read from the display memory, mapped by the transformation table to the desired intensity values, and then passed through the DACs to the television-like display monitor.

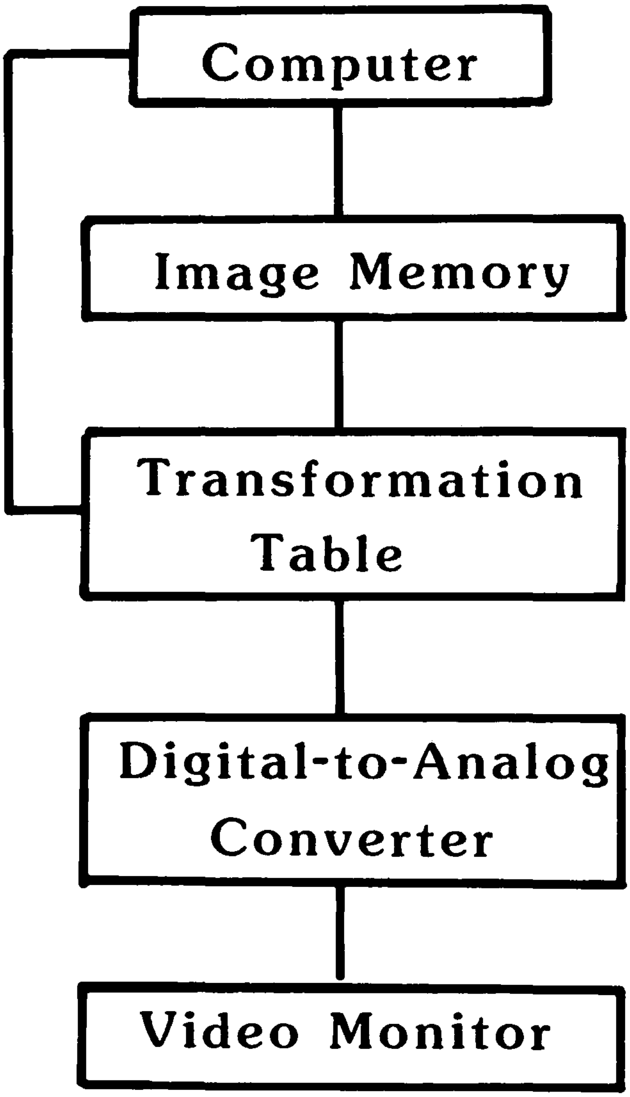

FIG. 5. The image display system contains its own memory for image storage as well as conversion tables for mapping the image values into desired display intensities.

The display contains its own memory so that the image can be refreshed on the display screen without interrupting the main computer or waiting for it to respond while performing some other operation. The transformation table is used to convert the raw data of the display to a range of intensities or contrast values that the operator believes may display image characteristics more clearly. This secondary memory or "look-up table" usually contains one memory location for each available intensity value in the display. It is used to map the image values into display intensities. As each image point or pixel is read from the image memory, its value is used as an address to locate its corresponding image intensity. This information is stored in the transformation table at the location where the address is equal to the value of the pixel being displayed. The DAC converts the digital value from the look-up table to an analog voltage, which in turn controls the intensity of the display. This relatively simple and logical mechanism actually provides a very powerful and versatile display capability. The use of the look-up table allows the display intensities to be modified quickly in complex ways without actually modifying the original image data. Modification of each point in the image matrix would require the recalculation 262,144 pixels for a 512 × 512 image, whereas the use of the look-up table only requires the recalculation of 256 values for a display with 256 gray shades.

Display characteristics vary with the particular manufacturer, but most modern displays present the image in a 512 × 512 display matrix. Clinical images that have been collected in smaller arrays are interpolated to the size of the display matrix. The 512 × 512 display provides a relatively smooth image with little of the "pixelation" effect that is present in coarser image arrays. The 512 × 512 matrix is the largest array that can be displayed on a television monitor using routine broadcast timing standards. The use of a broadcast standard allows the image to be transmitted to other relatively inexpensive display monitors throughout the department or hospital, and makes it compatible with standard video recording systems for archiving or clinical presentations. Using an even finer display matrix could possibly provide a smoother appearing image, but it would also entail a significantly more expensive hardware configuration with limited return in clinical utility.

The number of gray scales available in modern displays also varies somewhat from system to system, but 256 is the most common. The display, therefore, is capable of generating 256 separate and distinct analog intensities that correspond to the count capability of the image in which each pixel is 8 bits deep. In many nuclear medicine studies, this may be an excessively long gray scale, but it provides display capability for those clinical studies in which a very high quality display is required. Some early displays possessed only 16 gray shades. In these limited systems, the image quality was compromised by the appearance of contours.

Displays with artificially generated color have been popular since the beginning of computer applications. Color is available in most systems but tends to be of limited usefulness in most diagnostic situations. Generally, clinicians find the color display interesting but prefer high quality black and white for diagnostic uses. The interest in functional imaging, complex temporal analysis of cardiac examinations, and other studies that generate clinical results in both spatial and temporal dimensions has, however, generated a renewed interest in the diagnostic use of color. In these studies, images are generated that represent the time coordinate in color hues and the count values in intensity of the hues. In a time-to-maximum image for a bolus study, for example, the time of the occurrence of the maximum count rate in each pixel is represented by the color of the pixel; the actual value of the maximum is represented by the intensity of the color. Use of color requires a high quality display system and monitor. Limitations in the number of colors or hues tend to introduce the contours that limited the effectiveness of early black and white displays.

USER INTERACTION

The ability of the user to interact with the image is an important part of the system. It is often necessary for the user to outline anatomic regions as starting points for automatic analysis programs, modify computer-generated regions of interest (ROIs), and indicate points of interest in the images. There are a number of techniques available for providing these abilities; the three techniques commonly used are the joystick, the light pen, and the trackball (Fig. 6).

The joystick is familiar to anyone who has ever played a video game. It is a device that contains two potentiometers connected to a handle that is moved in the X and Y direction by the operator. The computer monitors the value of the potentiometers to determine the image location desired by the operator. A bright marker is placed on the image and moves as the operator moves the joystick. When the marker is satisfactorily positioned in the image, the operator indicates this to the computer by a separate pushbutton switch or through the console keyboard.

The light pen is a small hand-held wand containing a sensitive, focused light detector that the operator points at the region of the image to be marked. The output from the light pen is timed to the display while the image is painted onto the screen by the computer. As with the joystick, the region marked is indicated with a bright spot or figure.

The trackball is a smooth round ball mounted in the console table top. It spins freely in both the X and Y directions. While the operator moves the ball, a pair of pulse generators, one for the X axis and one for the Y axis, produce a stream of pulses that the computer counts. The number of pulses produced for each axis by the operator spinning the trackball is used to position the marker on the screen.

All three of these devices can be used for other control functions, such as adjusting image brightness or contrast or any other number of display features. The specific use of these devices depends solely on the software written to control the display.

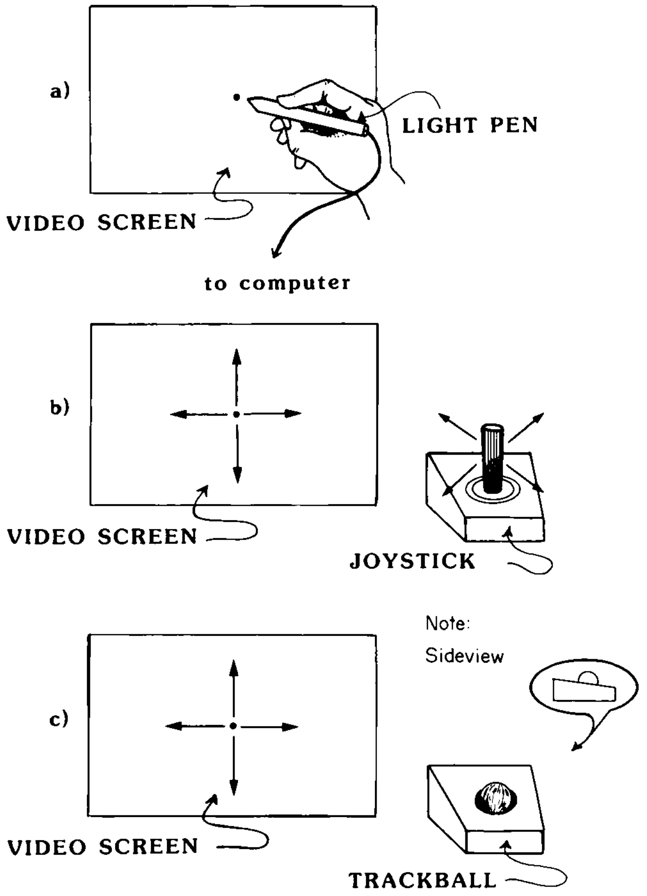

FIG. 6. The light pen, joystick, and trackball provide easily operated mechanisms for user interaction with the displayed image (*2*).

SPECT IMAGING

SPECT is a complex nuclear medicine procedure in which computers play an important part. In SPECT imaging, the computer collects images while the camera moves in a fixed pattern about the patient. Earlier versions of SPECT systems simply rotated the camera in a circular orbit about the patient. More recent versions are able to perform more complex imaging paths, ranging from simple elliptical orbits to following a complex body contour. Data are collected by the imaging system in one of two ways: "step and shoot" and continuous motion. In the step-and-shoot method, the camera head is moved progressively from point to point around the patient, and at each point the camera head is stopped and allowed to collect the image data. With the continuous motion method, the camera head never stops moving during data collection. This latter method requires more complex camera positioning electronics if the computer is to accurately locate the position of the head at all times.

The computer generally collects image data during the SPECT imaging procedure in a series of routine planar images, similar to an ordinary dynamic study. The relationship between an individual image and the location from which it is obtained is determined by the number of images collected and the total angular collection path (e.g., a 180° or a 360° rotation).

Two different system configurations are frequently encountered. In the first design, the camera is the controlling element and the computer simply acts as a data collection device. In the second design, the camera is used as an image input peripheral of the computer with its motion and data collection completely controlled by the computer. Although the configuration in which the computer is the master and the camera is the slave potentially offers the most versatility, there is little theoretical reason for choosing one configuration over the other if the specific system is properly designed.

In most commercial systems, the technologist has the option of choosing a number of collection parameters that affect the faithfulness with which the final tomographic images are produced. The number of steps in the collection procedure, the collection time per step, the digital matrix in which the planar images are collected, and the choice of data collection through 180° or 360° are the more common user-selected options. Typical values are 64 stops, 64 × 64 image matrix, and 360° collection for a standard clinical tomographic study.

SPECT systems are the most expensive routine clinical imaging devices found in a nuclear medicine department. The computer system alone commonly costs between $80,000 and $150,000.

DISTRIBUTED PROCESSING

The decreased size and cost of computational equipment coupled with the increased capabilities of modern electronics has given rise to a number of complex computer configurations. Previously, the usual method of handling data collection from a number of cameras in a laboratory was a combination of patient scheduling and mechanical switching of the camera connections to the computer. As costs decreased and the need for more efficient usage of the imaging facilities became evident, computers were often purchased for each camera. Duplication of hardware and a less than satisfactory clinical operation was the subsequent result. To overcome the limitations of separate unconnected computers, a number of multiuser configurations were developed. Although there is variance in the detailed operational and computational capabilities, the general concept of a multiuser distributed system is shown in Fig. 7. The core of the distributed system is usually a larger computer that controls the operation of the more expensive shared-system components and regulates the communication between the peripheral data collection sites and the central facility. The shared components of the central facility may be a powerful array processor or a number of large disk systems for patient data storage. The peripheral stations consist of smaller, less powerful computers that have limited computational capability and data storage.

In operation, the peripheral stations collect data from the scintillation cameras and store the images locally in their own disk or memory. With a sufficiently powerful peripheral system, collection and storage can be done completely independent of the other peripheral users. Consequently, the user has the impression of "owning" a single user system. Following completion of collection, the data may undergo preliminary analysis by the user or they may be transferred directly to the central processor for storage and made available for review or analysis by operators at other remote sites.

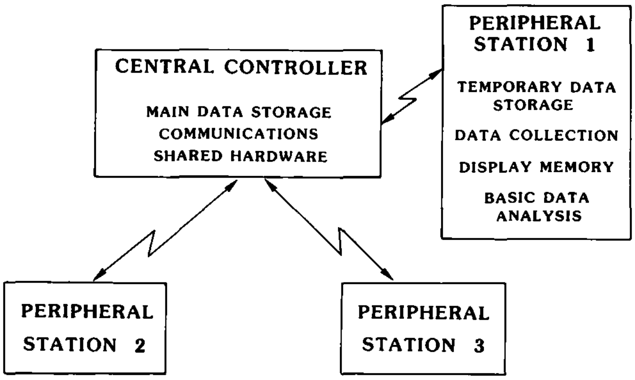

FIG. 7. The multiuser data collection and analysis system provides versatility, user sharing of central storage, and expensive image processing hardware as well as redundancy in the case of component failure.

Because there is only limited need at any one peripheral site for the availability of the powerful and expensive hardware, such as the array processor, expensive system components are often shared through the central system. Availability is on a time-shared basis with access being controlled either by a priority system or by a simple first-come, first-served mechanism. Postcollection data analysis is usually not affected by small delays in the availability of the central array processor. Although delays may be undesirable from the user's viewpoint, they will not affect the accuracy of the results. The cost savings provided by the sharing of expensive system components can be significant.

DIGITAL CAMERA

A number of manufacturers have introduced the "all-digital" camera. In some systems, the term "all-digital" simply refers to the imaging portion of the camera itself. However, the presence of the image in digital form in the camera makes it very easy to add computational capability. Although the boundary between the computer and the camera is very blurred in this device, it is worth considering. Although the one camera/one computer concept may be considered a step backward, the inclusion of the computer into the camera provides potential computer control of the entire imaging process. With the computer as an integral part of the imaging system, it is possible to perform complete clinical studies, including analysis, on the hospital floor. The need for hardwired connection to the central computer system in the nuclear medicine laboratory or the danger of not collecting an adequate patient study (which is only detected after return to the laboratory) is eliminated.

These computer systems are usually not programmable by the user and may be completely dissimilar to other computer systems in the laboratory. Consequently, the technologist is required to learn to operate a second system. In addition, the dedication of the computer to a camera can often represent an undesirable restriction to a clinical operation, especially if the computer cannot be used for analysis during data collection. The all-digital camera with the integrated computer system is a viable option for laboratories in which cameras are dedicated to specific imaging procedures such as renograms or cardiac ejection fraction.

CONCLUSION

The practice of nuclear medicine has been strongly affected by the evolution of the computer and its related hardware. Although this article has attempted to present a broad overview of the hardware of the computer system, the reader is advised to review the literature for the details of specific components and their application to clinical practice.

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