AN IMPROVED DATA RECORDER FOR SCINTILLATION CAMERAS

Richard D. Bliss, Paul M. Weber, and Leo V. dos Remedios

Riverside Bio-Engineering, Riverside, California and Kaiser-Permanente Medical Center, Oakland, California

A tape-recording system using a variation of pulse-width modulation records up to 28,000 Hz from an Anger camera without spatial or temporal distortion and with less than 1% data loss. Recording and playback may be made at any of five tape speeds: 3¾, 7½, 15, 30, 60 ips, each accommodating a different maximal counting rate. Since only two of four recording tracks are used, the others are available for other input. The replayed data appear in a format identical to the gamma camera signal; hence, any data manipulation performable on the original signal can be carried out on the replay. The system has advantages over other gamma camera recording systems: matrix artifact is eliminated; replay time may be accelerated or decelerated depending upon study objectives; when data are digitized for computer manipulation, data losses caused by deadtime are limited to those intrinsic to the gamma camera itself.

An ideal data storage system for the Anger camera would reproduce an image indistinguishable from the original in spatial resolution, data density, and data format. The formidable difficulties facing the designer of such a system are related primarily to the random nature and short duration of the events to be recorded. Most available systems rely upon conversion of the camera position signals to digital binary numbers after which the data are stored directly on tape or events are accumulated in a memory matrix for a period before the entire "frame" is recorded on tape. Early versions of the direct storage system were limited by long analog-to-digital conversion time, which increased the deadtime of the system and resulted in loss of data. The framing process permits a reduction of deadtime but temporal resolution is limited to the maximum available framing rate. In both cases, apparent spatial resolution is compromised by the introduction of a matrix artifact unless the number of sample points is large as all dots are reproduced in rows and columns.

Some of the original work in Anger camera data storage employed analog-recording techniques; that is, the data were recorded as a continuously variable signal, not as a discretely variable binary number. Results of early attempts to apply analog-recording methods were frequently unsatisfactory because of high data losses, resolution loss, or both. The narrow signal pulse width and the low recorder bandwidth of most small general-purpose instrumentation recorders make them incapable of recording the gamma camera position signals directly; therefore stretching the position pulses enough to permit satisfactory recording increases deadtime, causing data loss. Interchannel time-displacement errors or skew, a characteristic of all multichannel instrumentation recorders, frequently caused the X and Y coordinates to be shifted out of coincidence (*1*). Random amplitude inaccuracies in the signal reproduced by direct amplitude recording degrade image resolution. Frequency-modulation recording techniques have been used with some success to overcome the amplitude inaccuracies of the direct record process (*2*). Unfortunately, the FM record process has more restricted bandwidth and consequently higher data loss than the direct process at equivalent tape speeds.

Two observations contributed to the improved design of the machine described here: (A) The average rate at which clinical data are recorded is very much less than the theoretical maximum rate

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For reprints contact: Paul M. Weber, 280 W. MacArthur Blvd., Oakland, Calif. 94611.

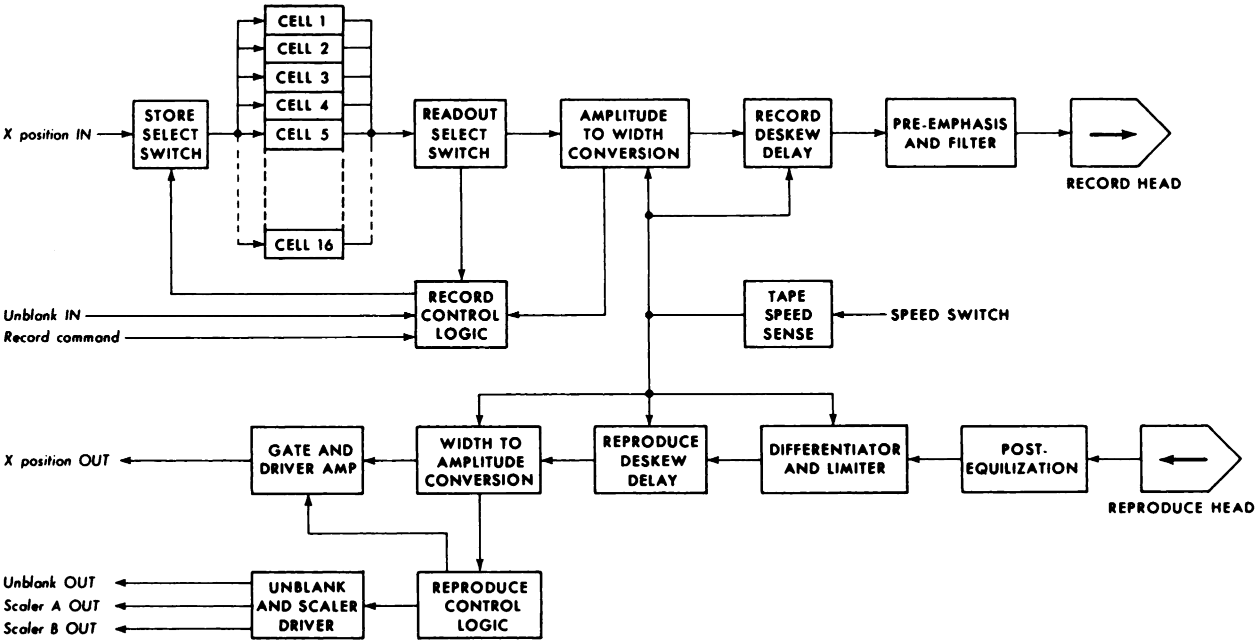

FIG. 1. Block diagram of analog recorder system. Signal-processing functions are shown only for x coordinate channel. y coordinates of image dots are processed in identical fashion and recorded on second data track.

of the gamma camera so that a machine capable of 30,000 Hz would be satisfactory in most applications provided that it caused no increase in camera deadtime. (B) A variation of pulse-width modulation offers greater accuracy than the FM technique and accommodates an increased data rate. Pulse-width modulation also obviates the need to record the Z (or unblanking) pulse because unblank timing is unambiguously defined by the signal.

The instrument described here is a high-speed version of the Riverside Bio-Engineering type 600D and is available as the model 700*. In both cases the tape transport is a modified laboratory type of instrumentation recorder. Data are recorded on two of four recording tracks on ¼-in. wide tape, the two tracks corresponding to the x and y coordinates of display dots. The other two tracks are available for other purposes and may be used for simultaneously recording additional data such as voice annotation, electrocardiogram, etc. The replayed data appear at the output in the same format as the gamma camera signal so that any data manipulation that may be performed on the original signal may also be done on replay. Recordings may be made at any of five tape speeds: 3¾, 7½, 15, 30, or 60 in./sec (ips). The higher speeds accommodate increased counting rates. The tape may be replayed in the forward or reverse direction and at any of the five speeds regardless of the original recording speed. The recorder interfaces to the Searle Radiographics Pho/Gamma III series of gamma cameras without requiring modification to either instrument but may be used to replay tapes independently of the camera. Without disabling the camera, the instrument may be removed (by disconnecting two plugs) for teaching or demonstration purposes or for use on another camera. Tapes are compatible from machine to machine so that data may be shared among users.

* Riverside Bio-Engineering, Riverside, Calif. The Model 600D is similar to the instrument described in this article except that the maximum tape speed is 15 ips and the corresponding maximum data rate without loss is 7,500 Hz. Tapes recorded on either machine may be replayed on the other.

METHOD

The input circuitry of the instrument consists of 16 pairs of analog memory cells similar to track-and-hold circuits (Fig. 1). The x and y coordinates of a scintillation event are stored in a pair of memory cells, which are then electronically tagged as unavailable for further storage until the information they contain has been recorded on tape. The next event is stored in the next pair of memory cells, the third event in the third pair, etc. The process continues as long as available storage cells remain to be filled, the event data being discarded if all of the 16 memory pairs are filled with unrecorded data. Information is removed from the memory and recorded on tape at regular intervals (i.e., at a constant rate) that depend on the tape-speed setting. As soon as the information stored in any particular pair of memory cells has been recorded, that pair again becomes available for storing new data.

Because the time required to store an event in the memory system (3.0 μsec) is much shorter than the camera deadtime (5–6 μsec), no data loss can occur unless all data storage cells are unavailable. For a 16-pair memory, the probability that no storage pair will be available is less than 1% for all counting rates less than 90% of the rate at which data can be recorded on tape.

The rate at which information can be removed from memory is the rate at which it can be recorded on tape. The slope of the pulse-width modulation ramp (and thus its repetition frequency) is determined by the tape-speed control. Memory readout, which is synchronized to the ramp frequency, advances one pair of cells with each sweep unless no data have been stored. Readout stops at the last pair of cells containing data, which will also be the first pair to receive new data when they occur. This arrangement minimizes the time required to transfer new information to tape. The shortest time required to record any event is 32.5 μsec at a tape speed of 60 ips. However, record time is inversely proportional to tape speed. The purpose of the memory is to derandomize the data and to reduce the effective deadtime of the recorder system to that of the scintillation camera for counting rates below the tape-recording data rate. Therefore at 60 ips data may be recorded at rates up to 28,000 Hz with less than 1% loss.

Data removed from the memory are converted to a pulse-width modulated signal before recording. The memory-amplitude voltage is converted to a variable width pulse by comparing the memory output with a linear voltage ramp, the slope of which depends on the tape-speed setting. The signal pulse begins when the ramp begins and terminates when the ramp voltage and memory voltage are equal (Fig. 2A). Thus the higher the stored memory voltage, the wider the resulting pulse. The variable-width pulse is filtered appropriately and recorded on tape. Conventional direct recording is used but with equalization and tape bias modified to optimize performance for the pulse-width modulated signal.

The reproduced signal from the tape is equalized appropriately and differentiated through a high-pass filter. Differentiating eliminates dc level shift at this point and reduces nonlinearities of the tape-recording process. A shaping circuit restores the variable-width pulse signal. The original amplitude is recovered by reversing the original modulating scheme (Fig. 2B). A linear voltage ramp is started at the leading edge of the signal pulse, and its amplitude sampled at the trailing edge. The ramp slope is again

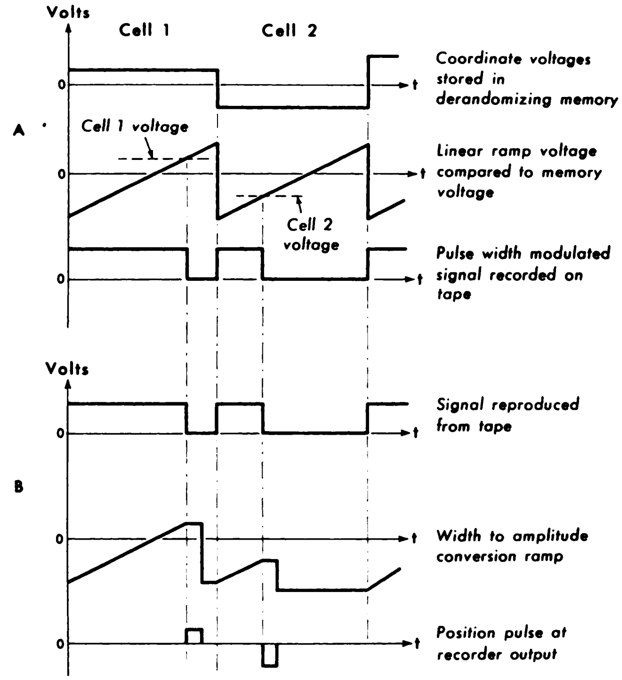

FIG. 2. (A) method of converting variable-amplitude position voltages to variable-width pulses. Signal voltage stored in analog memory is compared with linear voltage ramp. Output pulse begins when ramp resets, terminates when ramp voltage equals memory voltage. (B) method of recovering original amplitude from recorded width-modulated signal. Second linear-voltage ramp begins at pulse-leading edge and is stopped at trailing edge. Gating circuit shapes position pulses which resemble original camera signal.

a function of tape speed. At the completion of both x and y signals, the stored amplitudes are gated out as position signals to an oscilloscope, usually one of the gamma camera displays. An unblanking signal is generated and the dot is displayed in the usual fashion.

This tape recorder was connected to a conventional Pho/Gamma III H/P scintillation camera (Searle Radiographics), interfaced directly into a nuclear medicine computer system (MED II, Nuclear Data), and its performance was evaluated. The maximum counting rate possible with less than 1% data loss was measured directly at each available tape speed by progressively increasing the input counting rate. The percent loss was then calculated by relating the counting rate as displayed on the scintillation camera scaler after the recorded data on tape were played back through the camera console to the counting rate noted on the same scaler during direct data acquisition.

The effect of recording and playback on spatial resolution and distortion was also evaluated. Radioactivity in capillary tube test patterns was recorded directly into the computer system formatted in a 128 × 128-space matrix while the data were being recorded simultaneously on the tape.

One practical application of the tape recorder is to eliminate data loss due to relatively slow analog-to-digital conversion when studying rapid dynamic events. To test this capacity, recordings were made at data rates up to 28,000 Hz both on the tape recorder at 60 ips and digitally through the computer system. The data recorded on tape were then digitized at 3¾ ips. The results were compared with the directly digitized data.

RESULTS

Confirming the theoretical calculations, there was no significant data loss at each tape speed until the counting rate reached a maximum, at which sudden saturation occurred (Fig. 3). Losses were less than 1% with input rates up to 28,000 Hz recorded at 60 ips, up to 14,000 Hz at 30 ips, up to 7,500 Hz at 15 ips, up to 3,750 Hz at 7½ ips, and up to 1,850 Hz at 3¾ ips.

Recorded data loss on playback at each speed was evaluated by recording at each speed at a variety of counting rates which were maintained below saturation for the respective tape-recording speeds. A typical example of these data for one set of counting rates is shown in Table 1. Data recorded at any speed could be played back at any speed without loss.

When the data recorded on the tape were played back into the computer into similar space matrices, there was no significant distortion. Slight variation in the number of counts in each matrix cell was noted, mainly as the result of spatial displacement; but the spatial distortion was clearly less than 1%.

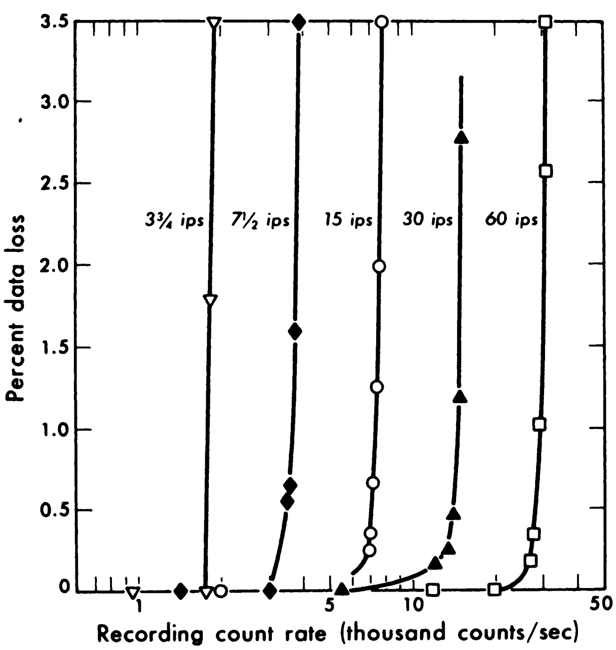

FIG. 3. Percent data loss is shown as function of input counting rate from scintillation camera for each recording speed. Data loss remains insignificant until near saturation when recorded counting rate rapidly approaches maximum value for each recording speed.

TABLE 1. EXAMPLE OF RECORDING DATA LOSS (PERCENT) FOR A VARIETY OF COUNTING RATES (HZ) AT EACH TAPE SPEED (IPS)

Recording: Tape speed	Recording: Counting rate	Percent loss on playback at various tape speeds: 3¾	7½	15	30	60
3¾	1,800	0.01	0.00	0.03	0.01	0.01
7½	3,570	0.65	0.65	0.65	0.63	0.65
15	7,140	0.67	0.67	0.67	0.68	0.65
30	14,000	0.48	0.48	0.48	0.47	0.48
60	28,000	0.35	0.35	0.35	0.35	0.35

The 16-fold tape-speed reduction eliminated all data loss in analog-to-digital conversion.

DISCUSSION

There are several potential sources of significant error throughout the system. The analog memory cells produce offset voltages which contribute displacements of the image dots. These offsets are adjusted to less than 10 mV maximum or 0.25% error for a typical ±2-volt position signal. An additional 0.1% error is introduced during conversion to pulse-width modulation and back again, principally by nonlinearities in the reference ramps and the recording process. The major disadvantage of the pulse-width modulation technique is its sensitivity to tape-speed variations, which constitute the largest single source of error. The most serious errors of this type are the result of minute distortion of the flexible tape as it passes over the record and reproduce heads, causing a short-term pulse-width variation known as "jitter". Jitter is responsible for about one-half of the relative position error produced by this instrument. Long-term speed variations cause image displacement and changes in image size. Tape-speed errors are minimized by use of tape transports with less than 0.5% cumulative velocity error. Minor additional errors are contributed by noise, tape imperfections, misalignments, and other sources. Typically, total cumulative dot displacement is ±0.5% maximum, less than ±0.25% average, as measured by a test signal of constant amplitude. Thus, a particular dot has a 50% chance of being displaced less than ±0.25% from its original position and a 99% chance of being displaced less than ±0.5%.

The system is nearly insensitive to dropouts of as much as 75% but does not reproduce data below this level. Therefore severe dropouts result in data loss rather than position error. Typical data loss resulting from tape dropouts is 0.001%, which is insignificant in most applications. The instrument is moderately sensitive to tape type. Use of an inappropriate or low-quality tape may drastically increase

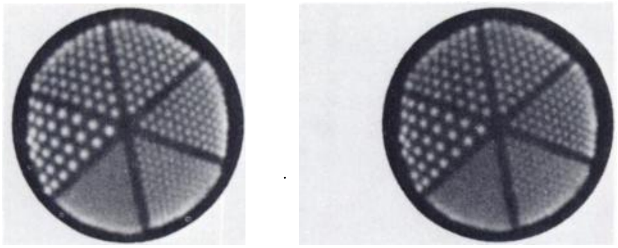

FIG. 4. Test patterns: (left) Original data from scintillation camera; (right) recorded first and photographed on playback. No distortion or loss of spatial resolution can be seen.

data loss. Only instrumentation tape yielded consistently satisfactory results although high-quality audiotape may be used for studies recorded at the lower speeds.

In addition to displacements of the dots relative to each other, errors cause image displacement, variations in image size, or image distortion. Long-term speed variations introduce both displacements and size changes. The amplitude-to-pulse-width conversion voltage ramp (record) must have the same slope as the width-to-amplitude conversion ramp (reproduce), or similar imperfections result. Nonlinearities in either the ramps or the tape-recording processes induce distortion of the image equivalent to barrel or pincushion distortion in optical systems. All of these errors are minimized by careful circuit design and by calibration before installation.

Skew, a property of tape-recorder heads, introduces an interchannel time-displacement error. Static skew results when the heads do not lie on a single line perpendicular to the direction of tape motion in the plane of the tape. To ensure that the tapes will be compatible from machine to machine, it is necessary to correct the tape for skew: before recording, the signal in one channel is delayed relative to the other. Deskewing delays are also applied to the reproduced signals to insure that the x and y coordinates appear simultaneously. One of the advantages of pulse-width modulation is that relatively simple deskewing circuits are required; delaying a variable amplitude signal is more difficult.

This system offers a number of advantages over previous approaches. There is no matrix artifact and photographs made from recorded data are visually identical to the originals (Fig. 4). Polaroid scintigraphs made from digitized data lose apparent data density and contrast because closely adjoining dots are forced into a single site and thus become indistinguishable from a single dot on the narrow-latitude Polaroid film.

The multiple-speed capability allows useful expansion or compression of replay time for rapid review of slow kinetics or careful checking of rapid kinetics. When the instrument is interfaced to a computer, a 16-fold increase in frame rate may be achieved by recording at the highest speed (60 ips) and replaying into the computer at the slowest (3¾ ips). The time separation between events is partially regularized by the derandomizing process; therefore losses due to long analog-to-digital conversion time are reduced during digitization of replayed data, particularly at the lower tape speeds. For example, events are separated by at least 200 μsec at 3¾ ips. Since the image is recorded as separate events rather than as a matrixed population, temporal resolution is preserved. Additional recording capacity is available in the two extra tracks on the tape not required for scintigraphic data. The system may be adapted to wider tape for increased auxiliary capacity. Half-inch and 1-in. tape-conversion kits for the tape transport are available from the manufacturer (Honeywell Instruments Division).

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