TECHNICAL NOTES

A Precision Pump for Simulated Cardiographic Studies

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A system simulating physiologic and pathologic changes in left-ventricular volume is presented. Its purpose is to provide a model to establish the accuracy of current equipment for assessing a heart's performance where the actual volume and size are measurable. The versatility of the model allows a wide range of variability of various parameters for simulation of many clinical situations.

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Considerable variations in the ejection-fraction results are frequently observed when more than one current nuclear cardiology method is used.

This prompted us to develop a pump that can accurately reproduce the typical volume changes of the left ventricle in order to test various parameters of the camera-computer system, evaluate errors and, where possible, minimize them.

THE SYSTEM

A rubber balloon represents the left ventricle (Fig. 1,B). Some variation in shape and rigidity of the balloon can be achieved by building up the wall with rubber cement to simulate a left-ventricular cavity. Areas of akinesis can also be simulated.

The balloon is placed in a water bath in an acrylic container roughly the size of the chest.

The pump consists of an acrylic cylinder, 5 cm in diameter calibrated in 2-cc divisions (Fig. 1,P). A stainless steel piston fits into the cylinder, with "O" rings providing an airtight seal. The balloon and pump are connected with an acrylic tube, 2 cm i.d., fitted with a stopcock for filling the system.

A linear motor (Fig. 1,M), like those used in computer disc drives, is axially coupled to the pump's piston. Instantaneous piston position is sensed by a linear slider-potentiometer (Fig. 1,Po) coupled to the piston. Since the cylinder diameter is constant, the connecting tube rigid, and water incompressable, the volume of fluid pumped is directly proportional to the change in position of the piston.

The drive unit (Fig. 1,D) powers the motor in a closed-loop control mode where the potentiometer voltage is constantly compared with an input waveform voltage. Any voltage difference is amplified to power the motor and move the piston to a position proportional to the input voltage. Input voltage can be scaled to produce a desired stroke volume, and a dc offset voltage added to set the quiescent piston position and end-systolic balloon volume. The potentiometer voltage is provided as an output to the recording equipment to monitor volume changes. Additional controls limit piston travel to prevent mechanical damage and provide a calibrated variable voltage to simulate an input signal.

A waveform generator (Fig. 1,W) provides a signal to the drive unit. Complex analog waveforms, each with 256 sample points and 8-bit amplitude resolution, can be stored concurrently. Usual practice is to store one cycle of the desired waveform. A ninth bit is stored for each sample point and used independently as a flag to represent an event such as the R-wave peak. Data are entered into memory using eight data switches and are reviewed with a hexadecimal display. A battery is used to maintain the contents of the memory when ac power is removed.

Analog waveforms are generated by sequentially scanning one page (256 bytes) of memory, as selected by a front-panel switch, and converting each 8-bit number to its respective voltage with a digital-to-analog converter. A voltage-controlled oscillator produces a continuously variable clock frequency that drives an 8-bit binary counter. The counter output is used to address memory. Control logic provides the option of letting the counter run con-

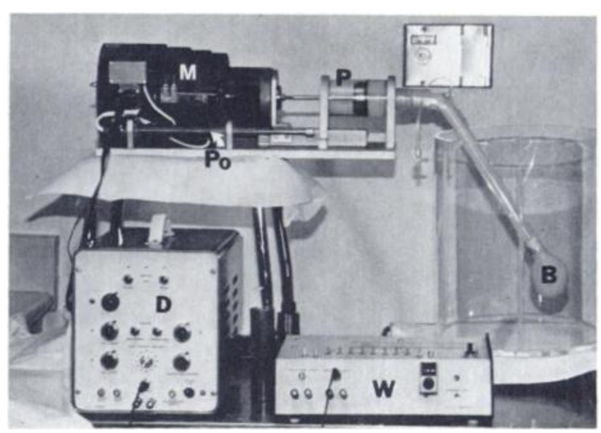

FIG. 1. B = balloon, P = pump, M = motor, Po = linear potentiometer, D = drive unit, W = wave generator.

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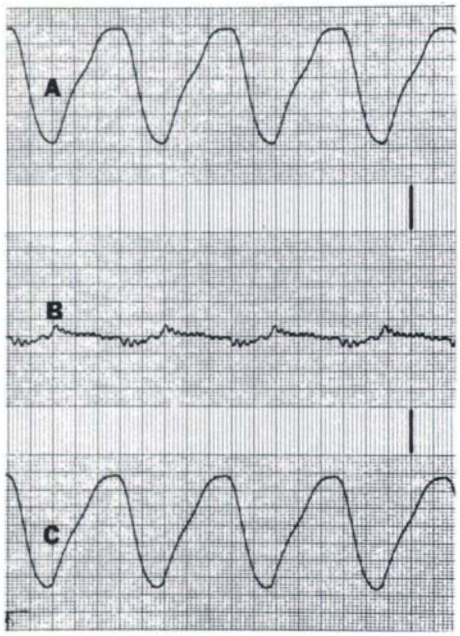

FIG. 2. Volumetric curves obtained at 60 cycles/min and 65-cc stroke volume. (A) Performance of the pump. (B) Difference between input signal and pump performance expanded four times. (C) Input signal from wave generator.

tinuously to create a periodic waveform, or cycle only once to create a single waveform. Front-panel scaling of the oscillator frequency is in cycles per minute. The current version of this generator does not provide for sinus arrhythmia, but such a feature is technically feasible.

High frequencies generated by the fast slew rate of the digital-to-analog converter are removed with an active low-pass filter that also provides a low output impedance to attached equipment.

OPERATION

Normal physiologic and pathologic left-ventricular volume curves are stored in the wave generator's memories, and the heart rate and desired curve can be selected. The end-systolic volume and stroke volume are set in the drive unit. This can be verified visually in the pump scale and in the printout of the pump's performance. The pump and balloon are filled with water containing enough Tc-99m activity to provide count rates in the clinical range. A weaker concentration of Tc-99m in water is placed in the container to simulate background activity in the lungs and chest wall.

To provide accurate absolute balloon volumes, the balloon can be completely collapsed, establishing the zero volume in the calibrated pump. The balloon is placed in the tank in a position similar to the LV in a chest. This is not too critical, since patients' hearts vary considerably, as we have observed in a series of computed tomograms. The balloon is held within a certain range by means of Plexiglas sheets and polyethylene bags filled with the container fluid.

The gamma camera is placed at a typical distance in the desired projection to simulate a clinical situation. The experiments are then performed as if to meet a patient's needs except for (a) instead of the ECG R waves to trigger the gating of a new cycle, a signal is stored in the curve in the memory; (b) the pump can be stopped in systole, diastole, or any other phase for accurate measurements and better statistical counting; and (c) the specific activity can be increased beyond clinical limits if necessary.

RESULTS

Since a model can provide accurate volume data, a true value for ejection fraction can be compared with values obtained from the camera-computer system to verify its performance.

To verify the performance of the pump, calibration measurements were obtained (Fig. 2) from the memory input (Curve C), the output of the potentiometer of the motor-pump (Curve A), and the difference between curves A and C (Curve B). There was very accurate reproduction of end-systolic and end-diastolic volumes as seen in the peaks and valleys of curves A and C. Some lag (4%) in the initial "relaxation" and "contraction" phases was noted, represented in curve B, which represents the difference between A and C with a scale expanded four times. Part of this lag is apparently inherent in the electronic system (change in direction of the signal) and some to mechanical resistance.

Randomly selected pictures obtained with this system demonstrate random variations with low count rate in the simulated first-pass (Fig. 3) and wall-motion data; also in computed ejection fraction in a simulated gated pool (Fig. 4) with low volumes and parallel-hole collimator.

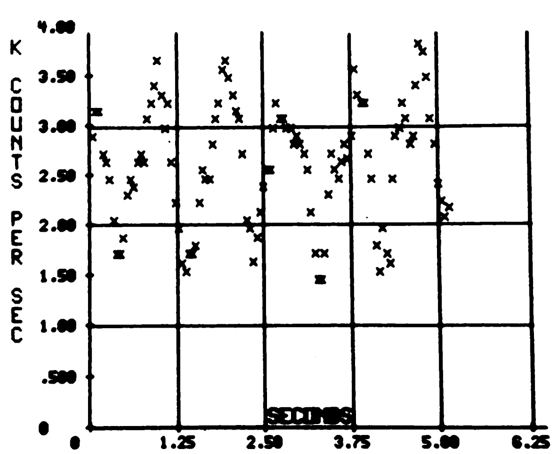

FIG. 3. Simulated first-pass acquisition at 60 cycles/min. Data points correspond to 0.1-sec intervals with 0.05-sec increments. Counts at end-systole points were as low as 146 (count rate of 1460/sec). True EF = 54%. Computer-calculated EF = 56%.

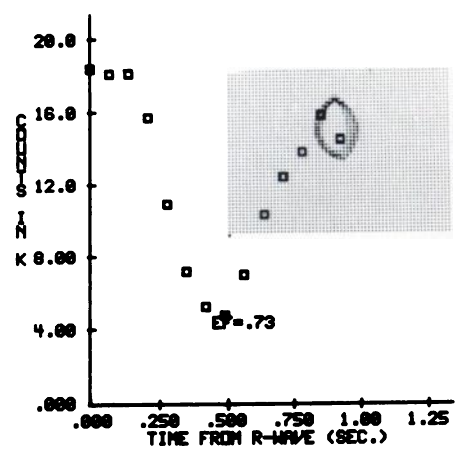

FIG. 4. Simulated gated pool acquisition at 60 cycles/min with framing rate of 0.07 sec/frame; acquisition time of 3 min; parallel-hole collimator. Count rate was ~4200/sec in systole. True EF = 75% (80 cc EDV and 20 cc ESV). Computer calculated EF = 73%.