Instrumentation for Computerized Heart Catheterization

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Abstract—An instrumentation scheme for performing computerized heart catheterization has been developed. Objectives in the development were 1) low cost, 2) stability, 3) reliability, and 4) simplicity of operation. These objectives were achieved by using integrated-circuit operational-amplifier techniques coupled with simplified noninteractive controls. Use of the equipment in four hospitals over the past four years on over 1500 catheterizations has shown it to be ideal for heart catheterizations and other clinical and experimental settings where cardiovascular measurements are made.

INTRODUCTION

COMPUTERIZATION of the heart catheterization laboratory presents some instrumentation and data acquisition problems. Our experiences over the past four years show the necessity for instrumentation that is stable and reliable but inexpensive and simple to operate so that a person with a minimum of instruction and training can use it.

Since all of the analog signals are sent to an analog to digital converter (ADC) (Redcor 663 series 100 kHz 10 bit) for processing by the computer (Control Data Corporation 3300), it is necessary to match the signal characteristics to the ADC. The ADC has an input range of −10 to +10 V for a full 20-V range with a 10-binary-bit resolution, or approximately 1 part in 1000. To make optimum use of the ADC resolution it is necessary to have signals span the full range. The instrumentation described here is optimized for this purpose. The amplification and signal conditioning are achieved locally in the catheterization laboratory for presentation on various displays and the computer terminal itself. The signals are amplified to a high level (± 10 V) locally to minimize transmission noise pickup problems. For the system described one ADC unit is about 20 mV. Noise pickup levels below 20 mV are easily achievable even over wire lengths of up to 1000 meters.

In general, the three types of controls that manufacturers supply with medical electronics equipment are 1) gain controls, 2) position controls, and 3) frequency selection. Since many of these controls interact and are set by trial and error procedure, only those controls that are absolutely necessary for operation of our system are placed on the front panel. Much of the initial setup and
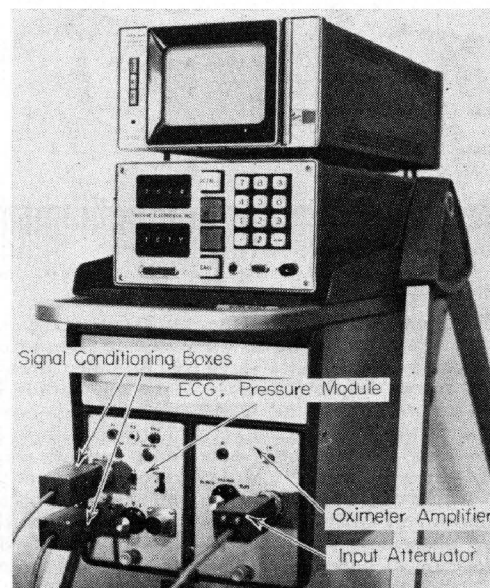
Fig. 1. Computer terminal and instrumentation configuration.

adjustment that normally goes into electronic instrumentation is built in and set very precisely by an electronic technician in the shop where the equipment is calibrated.

To provide ultimate utility and flexibility, the instrumentation is designed in modular units such that entire units can be replaced and interchanged (see Fig. 1).

The instrumentation amplifiers are primarily made from integrated-circuit operational-amplifier circuits (i.e., 709, 1437, and 741 types) with all signals being amplified from their low-level conditions to the high-level ± 10-V condition for transmission to the computer. This transmission is made either over hardwire connections or a telecommunications link [1], [2]. In either case, signals are conditioned for optimum use by the computer and by the telecommunication link by amplifying and adjusting the offset for full-scale capability of the computer's ADC and the communications link.

PRESSURE AMPLIFIER

Much of the data obtained during heart catheterization is from pressure transducers connected to catheters whose tips may lie in various locations of the circulatory system. Fig. 2 shows a schematic of the pressure transducer–amplifier system used in the heart catheterization, intensive care units, and research laboratories.
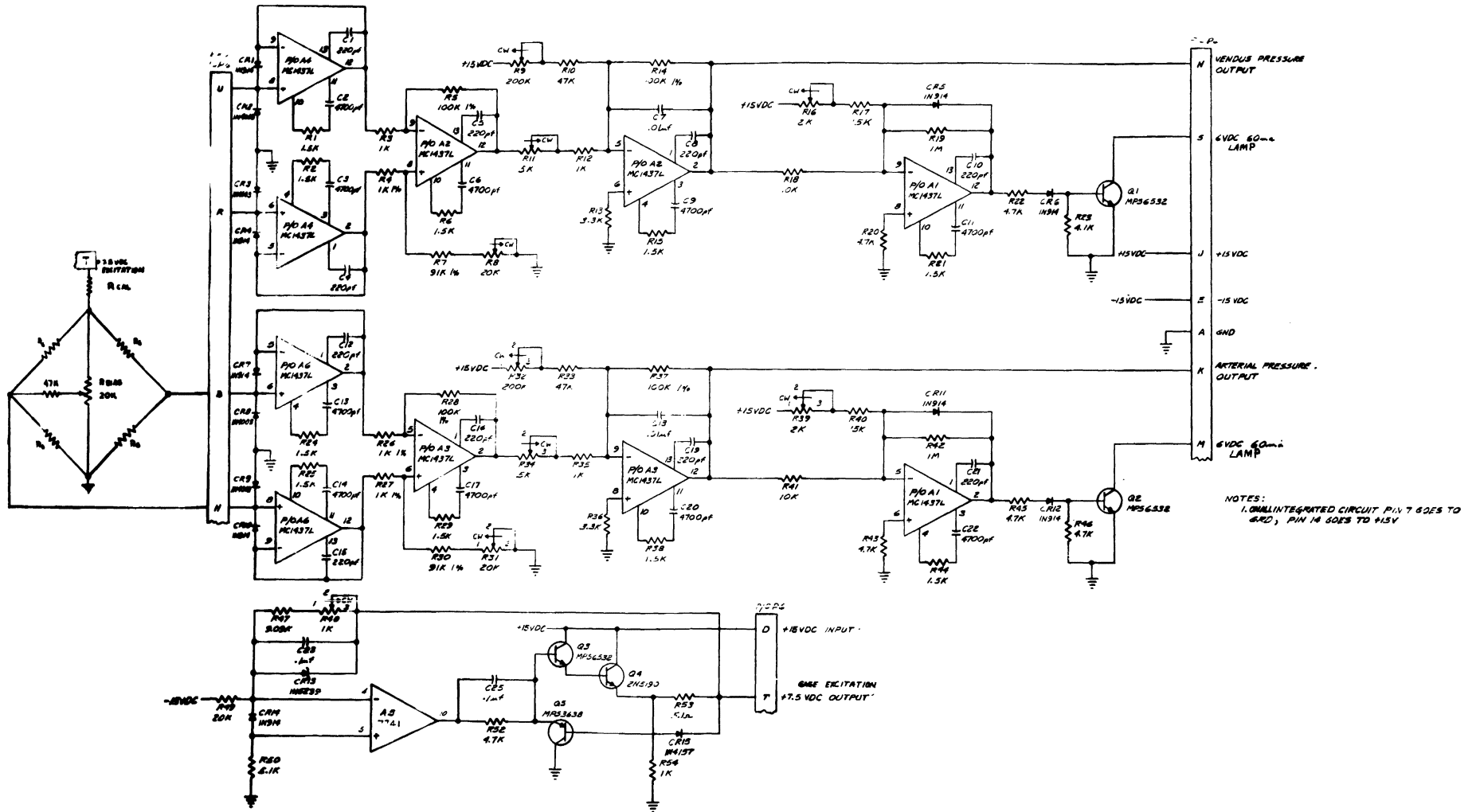
Fig. 2.   Dual pressure amplifier with excitation source.

Transducers used are standard Wheatstone–Bridge strain gages with four active elements. The gage excitation is dc and the amplifier is a high-gain dc amplifier; therefore, this system will not work with the variable reluctance type transducer.

For convenience and also to minimize the heating problems with the various type transducers used, a 7 1/2-V dc regulated power supply is built into each pressure-amplifier module. The supply derives its reference from the regulated (0.1 percent) ± 15-V supply used to power the operational amplifiers. A 15-V dc unregulated input is then regulated, using operational amplifier A5 and two power transistor drivers, Q3 and Q4, for transducer excitation. Current limiting is provided by Q5 and CR15. The output of the 7 1/2-V supply is then connected to resistor R_{cal} for adjusting the sensitivity of the gage. Each gage is calibrated in the shop before it is put into operation. The calibration factor chosen is 37.5 μV/mmHg (± 0.5 percent). Resistor R_{bal}, the 20K resistor in the bridge network, and the 47K resistor make up the balance network for the transducer (all the R_g are active gage elements). Each gage has a signal conditioning box (Fig. 1) that contains the internal sensitivity control (R_{cal}) and the balance resistor (R_{bal}). Resistor R_{bal} is the only external control needed to operate the pressure-amplifier system.

The amplifier shown in the schematic of Fig. 2 is for a dual pressure system. Since each section is identical only the lower section will be described.

In most cases a pressure range of -5 to $+195$ mmHg is used as the full-scale range. Using transducers with 37.5-μV/mmHg sensitivity, the full-scale 200 mmHg gives an input voltage change of 7.5 mV. Therefore, overall amplifier gain required is 2670. It is important that the amplifier have high gain and good temperature stability as well as high input impedance to prevent transducer loading. To achieve this high input impedance a noninverting operational-amplifier configuration is employed. These two amplifiers (A6) are integrated into one common silicon substrate that minimizes temperature gradients and associated differential temperature drift. The diodes between the positive and negative input are to prevent "lockup" of the operational amplifier when power is applied [3]. The diode from the positive input to ground is to provide protection during defibrillation and also to provide a source of current when the transducer is disconnected. In the usual operating condition, all four diodes are back-biased and can be considered to be out of the circuit. Amplifier A6 provides the necessary impedance transformation and drives the differential amplifier A3a (gain 100). Resistor R31 is a common-mode potentiometer used to cancel out 60-Hz common-mode signals. Amplifier A3b further amplifies the signal by approximately 27 (R34 adjusts) as well as providing offset and filtering characteristics to drive the cables to the ADC,
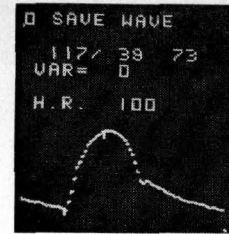

Fig. 3. Computer displayed results from an aortic pressure.

telecommunication link, display scopes, recorders, and other devices at the instrumentation site. Bias adjustment (R32) is used to compensate for offset in A6 and A3a as well as to provide a negative offset voltage. When the input bridge is balanced or the inputs to amplifiers are at the same potential, the bias control is adjusted to give an output of -9.5 V. This voltage adjustment is facilitated by use of level-detecting circuit A1. By setting R39 for input threshold of -9.5 V, this scheme will illuminate an indicator light on the front panel for outputs less than -9.5 V. The gain, bias, level, and common-mode potentiometer are internal adjustments.

A typical setup procedure for the gage would be as follows: the operator will plug the gage input socket and allow it to warm up for 3 to 5 min. With the gage exposed to zero pressure from a flush system, the balance potentiometer R_{bal} is adjusted until the indicator light on the front panel turns on, then is adjusted in the opposite direction until the light just goes off, achieving a setting of -9.5 V. Repeated settings of the balance control has shown that the baseline can be set to within 20 mV (1/10 mmHg for Statham P23Db and P37 transducers). This setup method is much simpler and more accurate and reliable than using a meter or an oscilloscope display for setting the zero point. Once this operation is completed the system is ready for use.

Fig. 3 shows a display from the computer terminal for an aortic pressure of a human subject during heart catheterization and shows typical computer results [4]. Values given are systolic pressure, diastolic pressure, and mean pressure in millimeters of mercury, and heart rate in beats-per-minute variance is displayed and used as an index of the representativeness of the sampled waveform.

Measurements of several amplifier–gage combinations show that drift over a three-day period in our laboratory environment (± 1°C) is less than 2 mmHg, which includes gage and amplifier drift.

Temperature characteristics were measured on both the amplifiers and transducers. For the temperature range from 20 to 40°C the amplifier has an offset or zero shift of 0.05 mmHg/°C while the Statham P23Db transducer has a zero shift of 0.5 mmHg/°C, and the Statham P37 has a zero shift of 1 mmHg/°C. Long-term stability of transducer sensitivity requires only intermittent (six month) checking of the transducers.
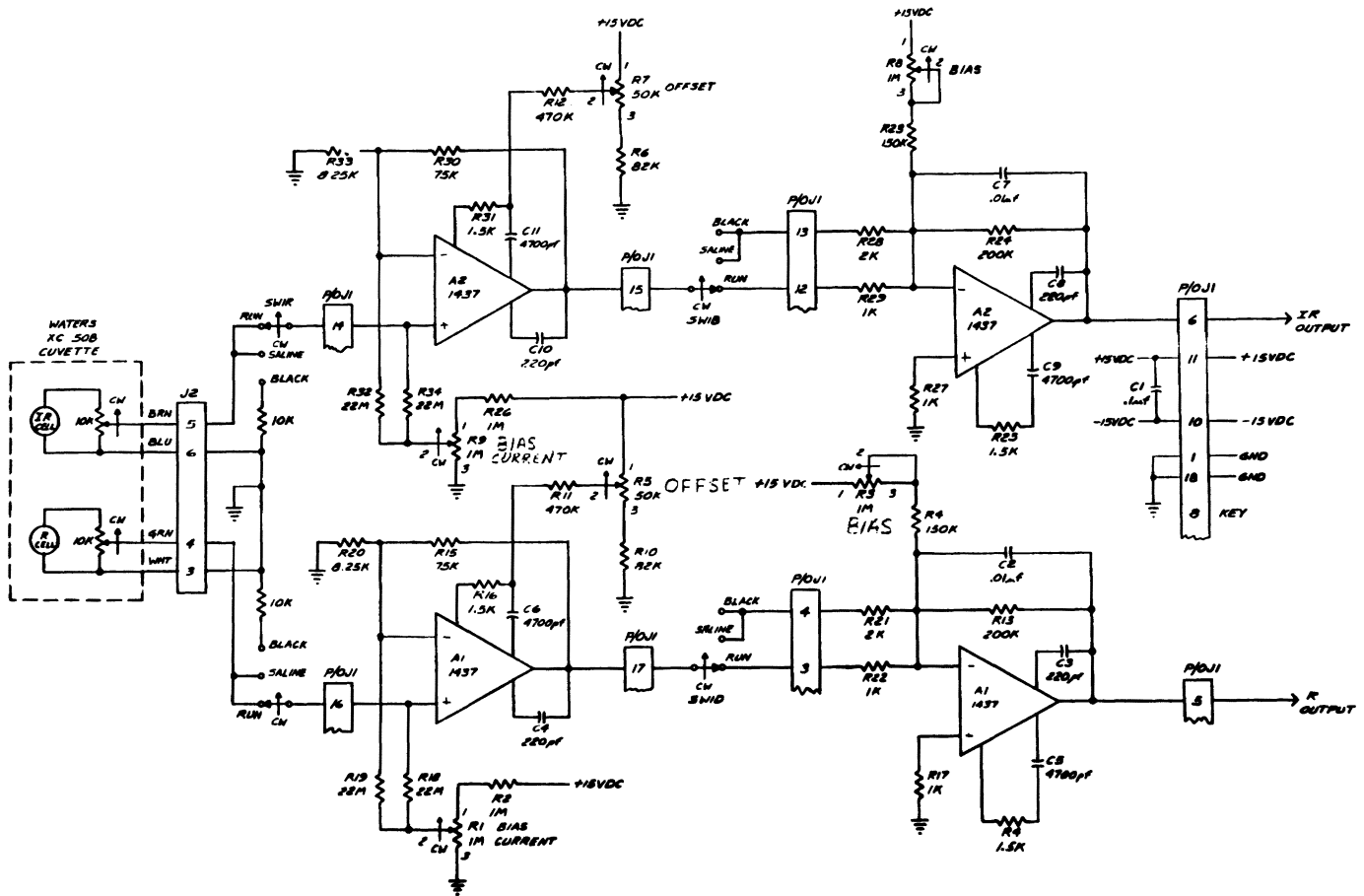
Fig. 4. Amplifier for cuvette densitometer.

The frequency response of the output amplifier is intentionally rolled off at approximately 150 Hz (by C18). This simple roll-off circuit attenuates high-frequency noise and permits sampling the pressure signal at 200 samples/s and minimizes aliasing [5].

ELECTROCARDIOGRAPHIC AMPLIFIER

Since it is necessary to have an electrocardiogram (ECG) with most cardiovascular measurements, and, indeed, it is necessary to monitor ECG continuously when probing the heart chambers with a catheter, an ECG amplifier was designed to be an integral part of the pressure-monitoring system. The computer uses the ECG primarily for R-wave detection, but the amplifier is designed such that it can be used for clinical evaluations [6].

The amplifier is of rather conventional design, and, therefore, not included in this presentation. The ECG amplifier is packaged in the same module as the pressure amplifier. The front panel controls have been minimized and include 1) a calibrate switch, 2) an ac reset switch, and 3) a gain control switch which provides for three fixed gains, 1000, 4000 and 10 000.

DENSITOMETER AMPLIFIER

There are two remaining parameters that are usually measured during a heart catheterization. These are blood–oxygen saturation and cardiac output from indicator dilution curves. Using the densitometer amplifiers and cuvette described, these two measurements can be obtained from a single instrument. The instrument used is a Waters XC50B cuvette densitometer that has been described by Wood et al. [7]–[9] and has been used in our laboratory for several years. Various attempts [10], [11] have been made to linearize this instrument. The approach taken with our scheme lets the computer perform the necessary linearization. For typical operating conditions the range of light-intensity change is very small, and the logarithmic conversion can be made with adequate accuracy by the computer rather than using complex electronic circuitry.

Fig. 1 shows a photograph of the input attenuator and cuvette amplifier. Fig. 4 is a schematic diagram of the dual-photo-cell amplifier. The 10K ohm attenuator is used to precondition the signal level from each densitometer. Since there is as much as a factor of 4 difference in sensitivity from one cuvette densitometer to another it is necessary to provide this variable sensitivity control.

The voltage developed across the 10K resistor is proportional to the current flowing through it, which, in turn, is proportional to the light intensity on the photo cell. The photo-cell signal is then brought to amplifier A1 through a selector switch (SW1) that has three positions, BLACK, SALINE, and RUN. In the BLACK position the input of the amplifier is switched through a 10K ohm resistor to ground and provides the baseline from which all subsequent measurements are made. In the BLACK position an attempt is made to set up a no-light level. It has been found that turning off the light source produces essential zero output from the photo cell. However, in this case the amplifier is switched rather than the light since several minutes are required for the temperature of the instrument to stabilize once the lights have been turned off. Amplifier A1a is a modified noninverting amplifier with a voltage gain of 10. Internal adjustment of bias current (R1) prevents output voltage due to changes of source impedance. The offset voltage of the amplifier is adjusted internally using R5. Amplifier A1b is a conventional inverting operational amplifier with a gain of 100 or 200, depending on the switch position (BLACK 100, SALINE 100, RUN 200). The entire amplifier is contained in one integrated-circuit package, a Motorola MC1437L. Amplifier A1b has an internal offset bias voltage adjustment (R3) to provide -9.5 V at the output when the switch is in the BLACK position. The feedback resistor R13 and capacitor C2 of amplifier A1b gives a roll-off of approximately 8 Hz, which is adequate for oxygen saturation and dye dilution studies and helps filter out pulsatile cardiac variation. Power for the light source of the densitometer is provided from a 4.75-V regulated supply which is similar to the regulated supply used for the pressure amplifier.

Calibration of the system is as follows: the control switch on the front panel is manually switched to the BLACK position. The computer then samples both the red and infrared cells for voltage reading and displays back to the operator the values taken in ADC units. The cuvette is then filled with a normal saline solution and switched to the SALINE position (gain 1000). The computer again samples the outputs. When calibrating the instrument in this way it is desirable to get full-scale sensitivity of the ADC by adjusting the 10K input attenuator. Changes in the sensitivity need only be made when components in the cuvette are changed. The calibration (BLACK–SALINE) of the densitometer is performed once for each catheterization to prevent problems of long-term change.

With this procedure completed the instrument is ready to measure oxygen saturation, and the switch is set to the RUN position (gain 2000). The change of gain by a factor of 2 was established following a series of clinical tests which showed that absorption of blood will typically put the red and infrared cells outputs at less than one-half full scale under a variety of clinical condi-
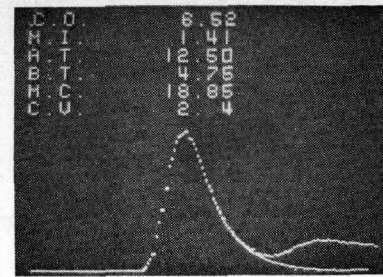
CO	cardiac output (l/min)
MI	mitral index
AT	appearance time (s)
BT	buildup time (s)
MC	mean circulation time (s)
CV	central blood volume (l)

Fig. 5.   Dye dilution curve results with actual and extrapolated curves.

tions. With the switch in the RUN position, the operator then draws blood through the cuvette, enters the appropriate location code through the computer terminal, and requests that the computer measure the oxygen saturation.

When using the instrument as a densitometer for measuring dye dilution curves, a two-point calibration is performed (0–12.5 mg/l), then blood is withdrawn (20 cm^3/min). Upon dye injection the computer begins to sample the output of the infrared amplifier 4 times/s. As the samples are being taken by the computer, each sample value is plotted on the computer terminal, giving positive feedback of correct sampling.

Computer results, along with recorded and extrapolated curves (Fig. 5), are displayed within 1 s after the dye dilution curve sampling is completed. Displaying of the measured and exponential curves is essential for determining whether the extrapolation has been carried out satisfactorily or if there are possible shunts. Background dye buildup from multiple dye curves in the same patient is compensated for by the computer.

The preceding procedure is simple to perform and is used in the heart catheterization laboratory, experimental laboratories, surgical suites, and intensive-care wards.

DISCUSSION

The instrumentation scheme described works extremely well in the computerized environment and meets the following objectives.

1) Inexpensiveness. A complete instrumentation scheme for heart catheterization, as shown in Fig. 1, can be built for a low cost of $500, which includes cost of parts, assembly, and adjustments but does not include transducers.

2) Reliability. Only quality components and operational amplifier feedback techniques are employed. Each amplifier system is also built on a modular printed circuit card so it can be easily exchanged.

3) Stability. The amplifier stability with both time

and temperature are significantly better than the stability of the transducers.

4) Simplicity of operation. A minimum number of controls are used.

More than 1500 computerized heart catheterizations have been performed using this equipment. Utilization of the concepts developed in the catheterization laboratory allows the conducting of complex physiological experiments in animal laboratories with a minimum of instrumentation difficulties. Clinical applications of the blood pressure scheme in monitoring critically ill patients is a typical extension of these instrumentation techniques [12].

ACKNOWLEDGMENT

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