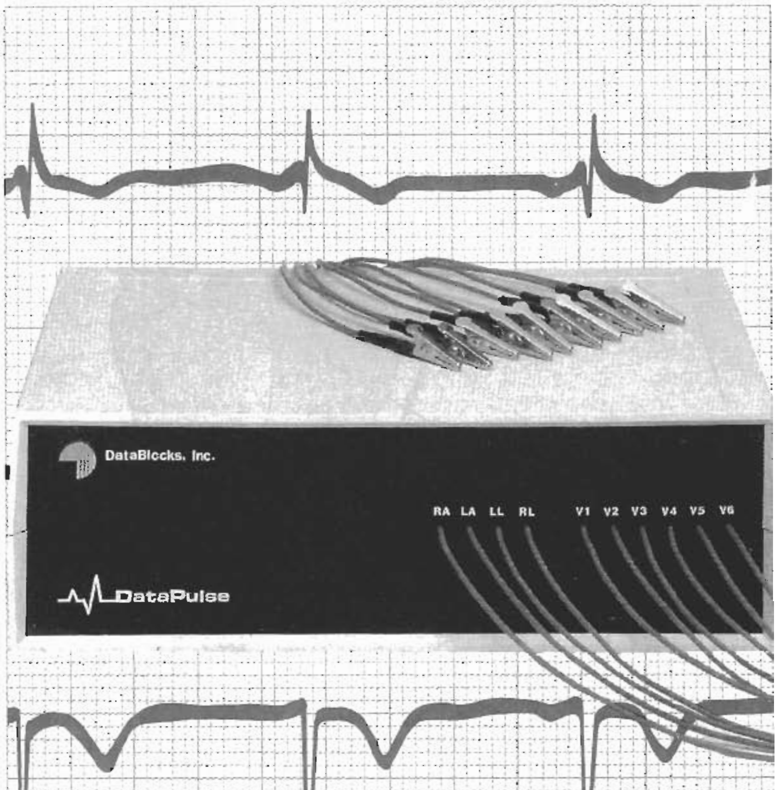
ELECTROCARDIOGRAPH



Keep an eye on your health and learn about medical electronics with the Radio-Electronics electrocardiograph.

H. EDWARD ROBERTS, M.D.

IF YOU'RE INTERESTED IN MEDICAL ELECTRONICS, OR just concerned about your family's health, then you should build the Radio-Electronics electrocardiograph. The electrocardiograms (ECG's or EKG's) it will produce can be analyzed by yourself or your doctor. We are not suggesting that you practice medicine using this device, but you should find it interesting and educational in monitoring your health. You will see some of the unique techniques used in medical electronics and you may be surprised to see how similar medical electronic equipment is to most other types of electronic equipment.

The electrocardiograph that we will build produces ECG's that are essentially identical to those produced by commercial machines costing $10,000 dollars or more. In order to keep our cost to a minimum we use a standard PC as an operator interface and output device. That way you can print out a hard copy of your ECG or just display it on your monitor.

Biological theory

In order to understand the electronic operation of an electrocardiograph, we need to understand some basic biological principles. As shown in Fig. 1, the heart consists of four chambers which are organized as two pumps—the so-called right and left heart. The right heart collects the blood returning from the body and pumps it to the lungs, while the left heart collects blood from the lungs and pumps it to the body.

Each pump has two parts: the upper chamber known as the atrium and the lower chamber known as the ventricle. The atrium collects blood between cycles and at the appropriate time contracts, filling the lower ventricles. The ventricles then contract and pump blood to the lungs or body.

The heart is controlled by a pulse generator, known as the pacemaker, located in the right atrium, which initiates cardiac action. It is analogous to the clock in a digital system. The pulse it generates is first sent to both atrium which causes them to contract, filling the ventricles. After a delay of approximately 150 milliseconds, the ventricles are then triggered by the same pulse, which causes them to contract. As in a digital system, the timing relationships are quite important and much of the disease associated with the heart is related to timing defects.

Figure 2 shows a typical signal as seen on an ECG. The first pulse, called the "P" wave, is generated by the pacemaker. The next pulse, called the "QRS complex," represents the electrical signal generated by the ventricles contracting. The "T wave" which follows the QRS complex is generated as the muscles of the ventricles relax, or repolarize.

A standard ECG consist of 12 channels; each channel "looks" at the heart from a different electrical axis. The different "views" allow us to interpret the activity of different parts of the heart. The timing relationships between different components of the heart will identify defects in the conduction pathways.

How ECG's are used

In patients with high blood pressure, the left ventricle will become quite large due to its in-

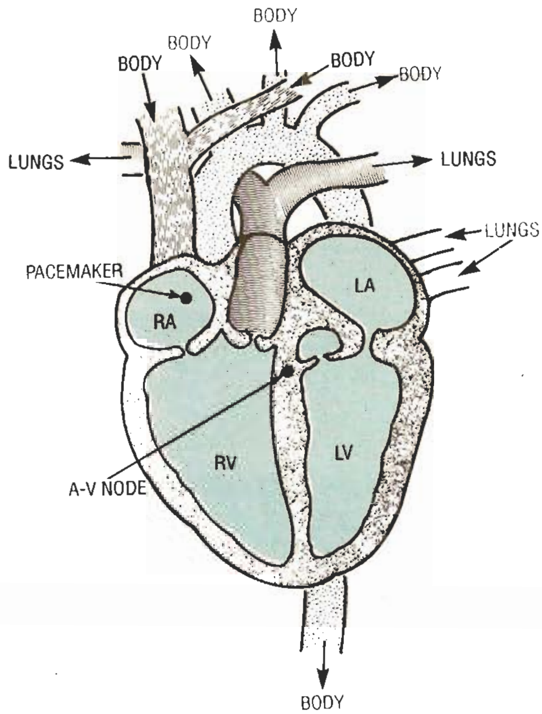


FIG. 1—THE HEART CONSISTS OF FOUR CHAMBERS which are organized as two pumps, known as the right and left heart. The right heart collects the blood returning from the body and pumps it to the lungs, while the left heart collects blood from the lungs and pumps it to the body.

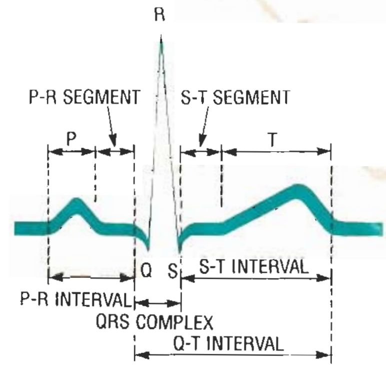


FIG. 2—A TYPICAL SIGNAL as seen on an ECG. The first pulse, called the "P" wave, is generated by the pacemaker. The next pulse, called the "QRS complex," represents the electrical signal generated by the ventricles contracting. The "T wave" which follows the QRS complex is generated as the muscles of the ventricles relax, or repolarize.

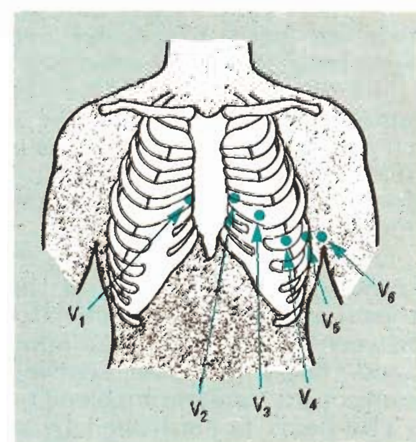


FIG. 3—TEN LEADS ARE CONNECTED to the patient in a 12-channel system: they are right arm, left arm, left leg, and 6 chest leads called the V leads. The right leg is used as a ground and as an input to reduce system noise.

TABLE 1—I/O PORT ADDRESS FUNCTIONS

Port Address	Control Pulse Function
52	Generates Clock for Multiplexer Sequencer
53	Generates Clear for Multiplexer Sequencer
54	Latches ECG Control Signal Byte in IC16
55	Latches Lead Offset Data in IC17

creased work load. That is seen as a significant increase in the amplitude of the QRS complex. Treatment of the high blood pressure will allow the left ventricle to return to normal size, which significantly decreases the chance of a heart attack.

Since the amplitude of the electrical signals in the heart are a function of chemicals in the body, it is possible to predict abnormalities. For example, an elevated potassium level will produce a tall peaked T wave.

If a portion of the ventricle is damaged, a so-called "Q wave" is formed which is simply a negative-going QRS complex. The location of the damage can be determined by noting which leads contain the Q wave. That's how a doctor can tell where you have had a heart attack.

Most normal individuals produce an extra, or irregular heart beat every now and then, which may occur in the top or bottom of the heart. It is a condition known as arrythymias. The irregular beats can be quite dangerous if they occur frequently or if they occur during certain intervals in the normal cardiac cycle. Many researchers believe that the most common cause of death in males is due to irregular beats occurring at a time such that they "scramble" the normal electrical timing in the heart—the situation is known as fibrillation.

Special ECG systems, known as Holter monitors, can detect these irregular beats. They are simply ECG's with one or more channels that store each of the 80,000 or so beats in one day. The data from the Holter is then fed into a computer which analyzes it for arrythymias. Similar monitoring equipment is used in ambulances and intensive care units for instantaneous analysis of irregular beats. Often this analysis is performed automatically by arrythymia detectors.

Another area of particular interest in ECG's is the "ST segment." That is the area between the QRS and the T wave. It is very predictive of obstructed arteries before any damage occurs to the heart. Obstruction of an artery will result in a depressed ST segment of the ECG—it will fall below the base line in the affected leads. The exercise cardiogram, or stress test, looks primarily at the ST portion of the ECG to predict if any of the heart's arteries are becoming clogged.

It is possible to become quite

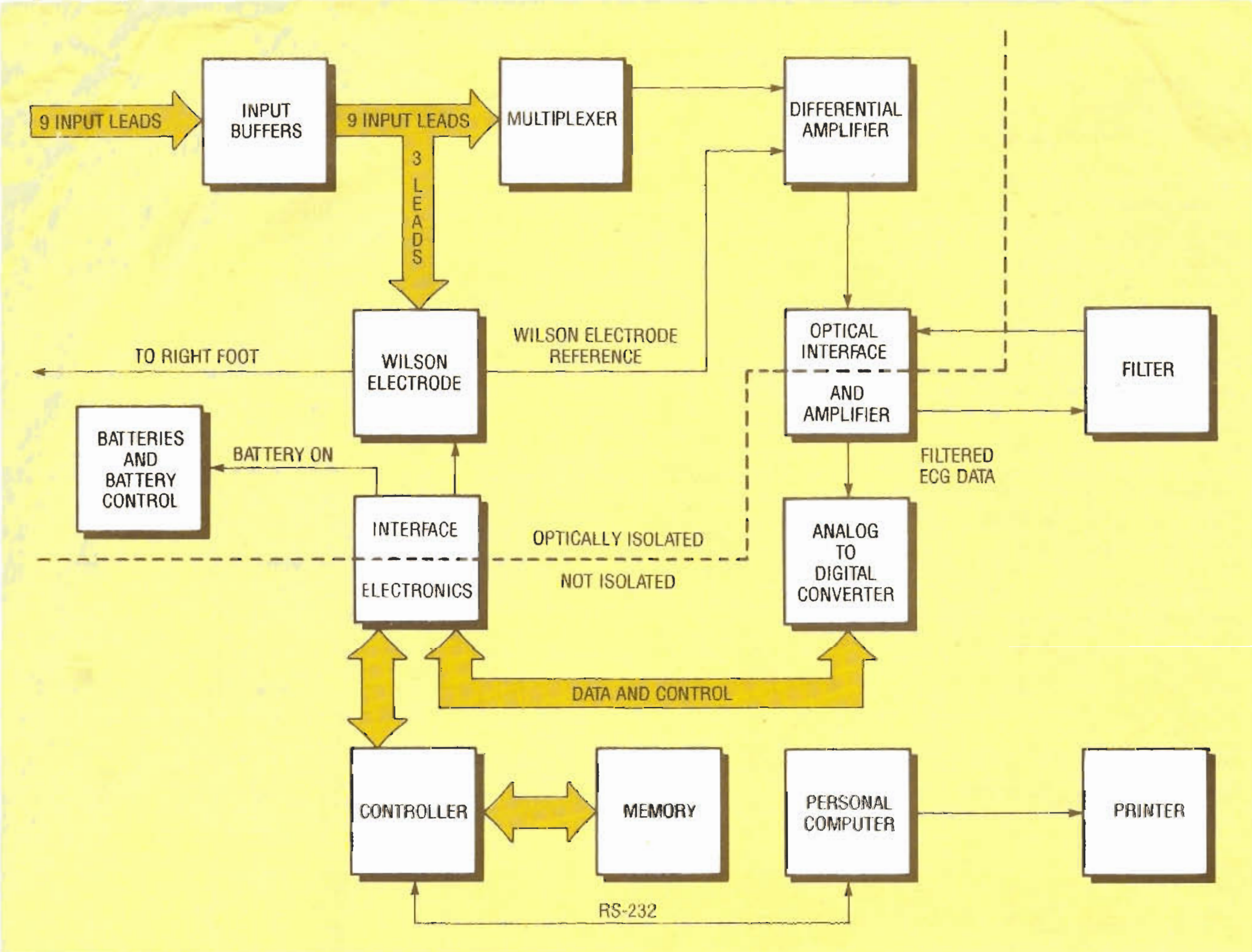


FIG. 4—BLOCK DIAGRAM OF THE COMPLETE ECG SYSTEM. The system logically divides into the front-end electronics and the controller. Data communication between the analog and digital portion of the ECG is accomplished through optical isolators, which helps keep the patient isolated.

PARTS LIST—CONTROLLER

All resistors are ¼-watt, 5%, unless otherwise noted.

R1—10 ohms
R2, R7–R10—10,000 ohms
R3–R6, R15, R16—1000 ohms
R11—7500 ohms
R12—24,000 ohms
R13—30,000 ohms
R14—10,000 ohms × 8, SIP

Capacitors

C1–C22, C25, C26, C28, C29, C33, C34, C42—0.47 µF, ceramic disk
C23, C24—22 pF, ceramic disk
C27, C30—0.001 µF, metal film
C31—220 pF, ceramic disk
C32—10 µF, 10 volts, electrolytic
C35, C38, C39,—10 µF, 10 volts, tantalum
C36, C37, C40, C41—1 µF, 10 volts, tantalum

Semiconductors

IC1—Z80 CPU
IC2–IC5, IC12—74HC245 bus transceiver
IC6, IC8—Altera EP320 PAL
IC7—Altera EP600 PAL
IC9—27C256 EPROM
IC10, IC11—55257 static RAM
IC13—74HC688 equality comparator
IC14—74HC138 1-of-8 decoder
IC15—82C52 UART
IC16, IC17—74HC573 octal latch
IC18—74HC74 dual D flip-flop
IC19—MC145406 RS232 transceiver
IC20—AD0829 A/D converter
IC21, IC22—DAC0830 D/A converter
IC23, IC24—NE5532A op-amp
IC25—74HC14 hex Schmitt inverter
IC26—74HC00 quad NAND gate
IC27—PS2501A-2 optoisolator
IC28, IC31—not used
IC29—ICL7660 DC-DC converter
IC30—78L06AC voltage regulator
IC32—7805 voltage regulator
D1–D4—1N914 diode
D5—5.1-volt Zener diode
D6—6-volt Zener diode
Q1—IRFZ10 N-channel MOSFET

Other components

XTAL1—2.4576 MHz crystal
XTAL2—8.00 MHz oscillator
S1—SPDT momentary contact switch
SO1—DB25 connector

Note: The following items are available from DataBlocks, Inc., Glenwood, GA 30428, (912) 568-7101.

- **Design package including schematics, assembly instructions, and checkout- and plot-software design specifications (ECG-DP): $27.00.**
- **Front-end PC board, controller PC board, and design package from above (ECG-PC): $74.00.**
- **Complete kit of parts, including both PC boards, IC's, sockets, passive components, design package, ECG software, and checkout software (ECG-KIT): $289.00.**
- **Lead kit consisting of 50 feet of 29-gauge shielded cable, 10 alligator clips, heat-shrink tubing, and instructions (ECG-LD): $53.00.**
- **EPROM containing ECG software, ECG resident portion of checkout software (ECG-PROG): $45.00.**
- **Set of four programmed PAL's (ECG-PAL): $67.00.**
- **Case as shown with mounting hardware (ECG-CASE): $29.00**
- **Package of 100 self-adhesive electrodes (ECG-EL): $20.00.**

Please include $5.00 shipping and handling for design package and electrodes, $10.00 shipping and handling for all other products. Georgia residents must add sales tax.

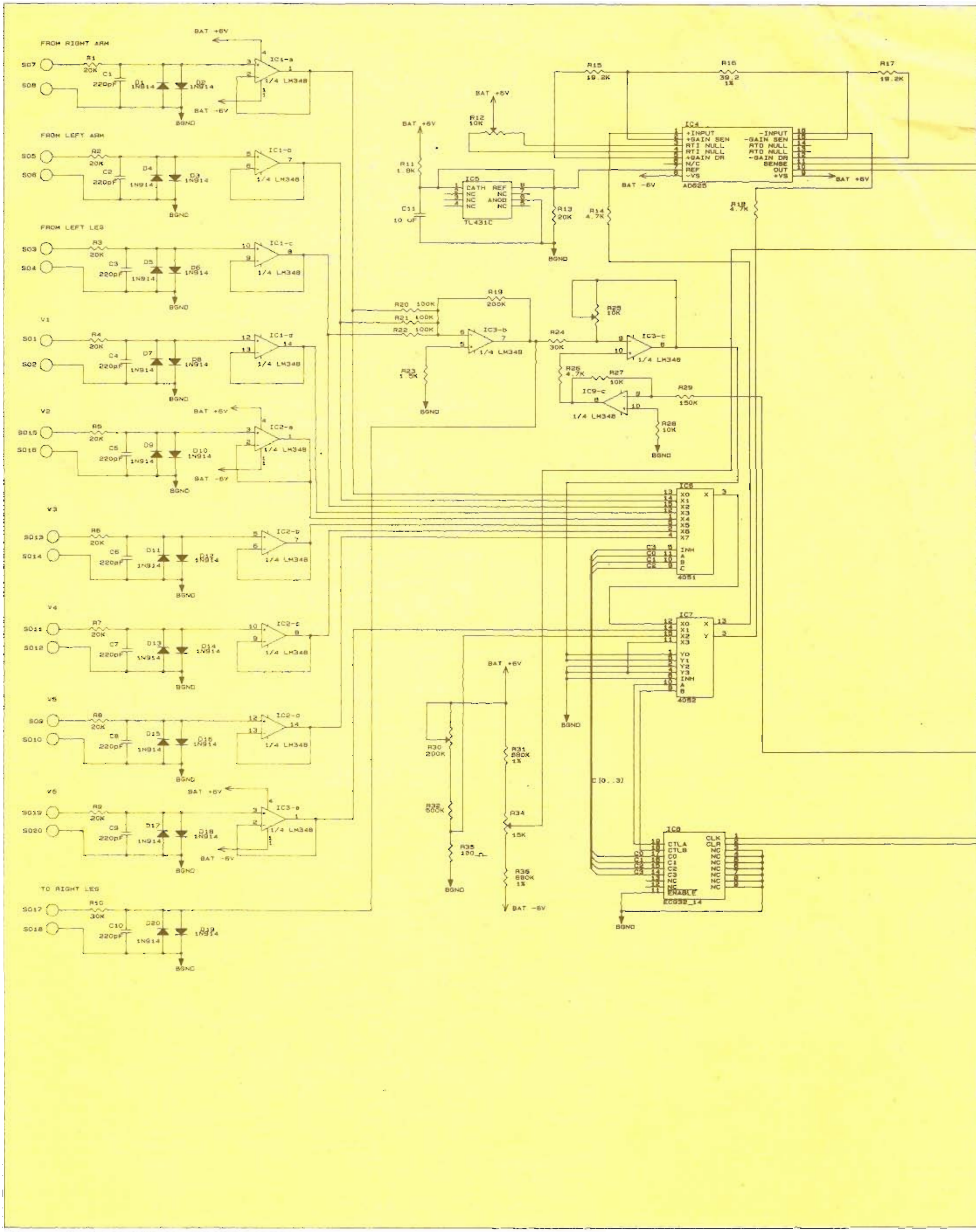
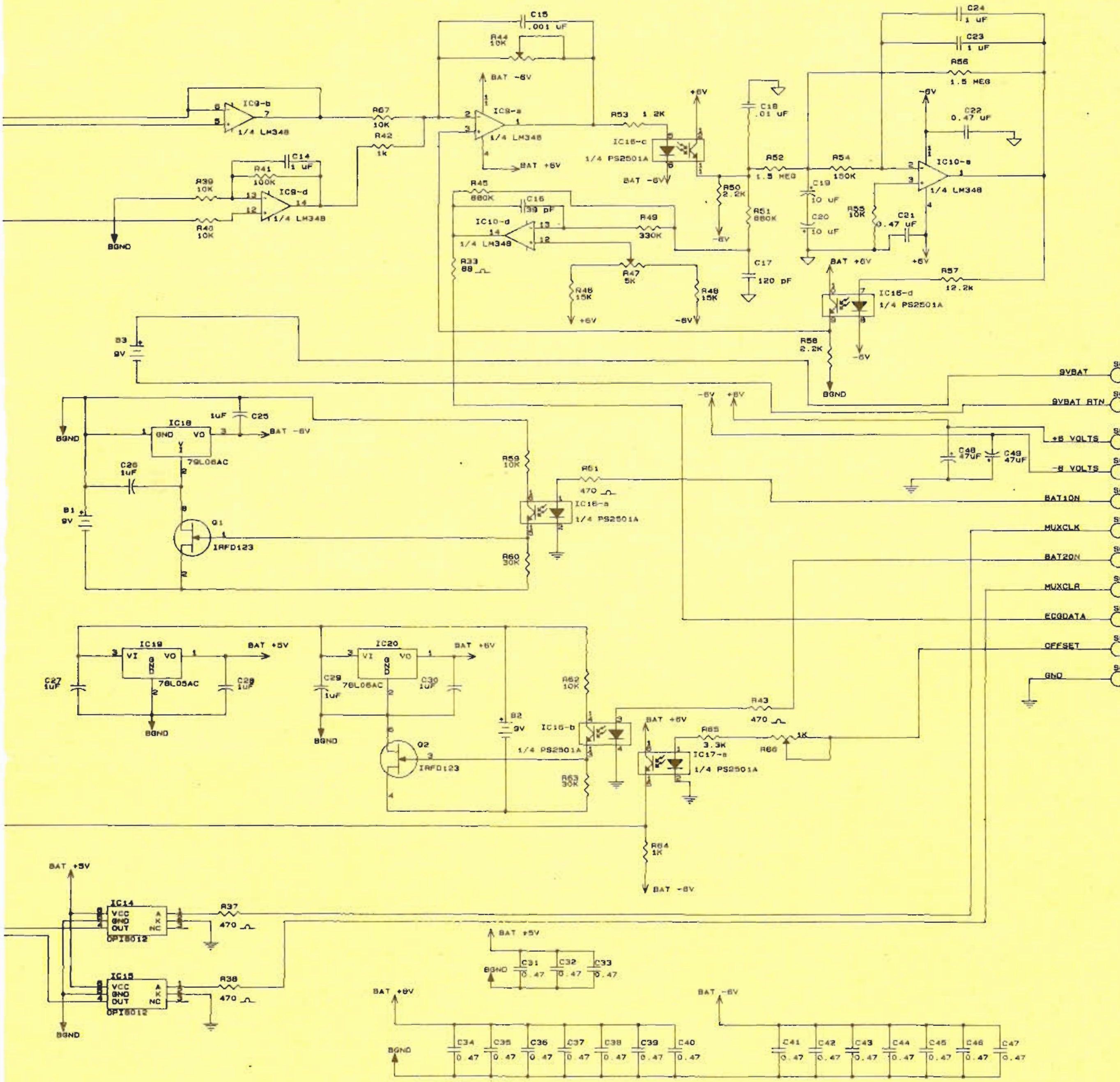


FIG. 5—THE FRONT-END ELECTRONICS takes in the signals from the 9 input leads located on the patient. The small signal from each of the leads is fed into the quad op amps IC1, IC2, and IC3-a.



C15 .001 uF
R44 10K
BAT -6V
BAT +6V
IC9-b 1/4 LM348
IC9-a 1/4 LM348
IC9-d 1/4 LM348
R67 10K
R42 1k
C14 1 uF
R41 100K
R39 10K
R40 10K
BGND
R53 1.2K
IC16-c 1/4 PS2501A
C18 .01 uF
R52 1.5 MEG
R54 150K
R50 2.2K
R51 680K
C17 120 pF
C19 10 uF
C20 10 uF
R55 10K
C21 0.47 uF
C24 1 uF
C23 1 uF
R56 1.5 MEG
C22 0.47 uF
IC10-a 1/4 LM348
R45 680K
C16 39 pF
IC10-d 1/4 LM348
R49 330K
R33 68
R47 5K
R46 15K
R48 15K
R57 12.2K
IC16-d 1/4 PS2501A
R58 2.2K
B3 9V
9VBAT
9VBAT RTN
+6 VOLTS
-6 VOLTS
BAT1ON
MUXCLK
BAT2ON
MUXCLR
ECGDATA
OFFSET
GND
S021
S031
S022
S023
S024
S025
S026
S027
S028
S029
S030
C48 47uF
C49 47uF
IC18 78L06AC
C25 1uF
C26 1uF
B1 9V
Q1 IRFD123
R59 10K
R61 470
IC16-a 1/4 PS2501A
R60 30K
IC19 78L05AC
BAT +5V
C27 1uF
C28 1uF
IC20 78L06AC
C29 1uF
C30 1uF
B2 9V
Q2 IRFD123
R62 10K
R63 30K
IC16-b 1/4 PS2501A
R43 470
R65 3.3K
R66 1K
IC17-a 1/4 PS2501A
R64 1K
IC14 OPI8012
IC15 OPI8012
VCC
OUT
R37 470
R38 470
C31 0.47
C32 0.47
C33 0.47
C34 0.47
C35 0.47
C36 0.47
C37 0.47
C38 0.47
C39 0.47
C40 0.47
C41 0.47
C42 0.47
C43 0.47
C44 0.47
C45 0.47
C46 0.47
C47 0.47

PARTS LIST—FRONT-END

All resistors are ¼-watt, 5%, unless otherwise noted.

R1–R9, R13—20,000 ohms
R10, R24, R60, R63—30,000 ohms
R11—1800 ohms
R12, R25, R44—10,000 ohms, potentiometer
R14, R18, R26—4700 ohms
R15, R17—19,200 ohms
R16—39.2 ohms, 1%
R19—200,000 ohms
R20–R22, R41—100,000 ohms
R23—1500 ohms
R27—910 ohms
R28, R39, R40, R55, R59, R62, R67—10,000 ohms
R29, R46, R48—15,000 ohms
R30—200,000 ohms, potentiometer
R31, R36—680,000 ohms, 1%
R32—500,000 ohms
R33—68 ohms
R34—15,000 ohms, potentiometer
R35—100 ohms
R37, R38, R43, R61—470 ohms
R42, R64—1000 ohms
R45, R51—680,000 ohms
R47—5000 ohms, potentiometer
R49—330,000 ohms
R50, R58—2200 ohms
R52, R56—1.5 megohm
R53—150 ohms
R54—150,000 ohms
R57—12,200 ohms
R65—3300 ohms
R66—1000 ohms, potentiometer

Capacitors

C1–C10—220 pF, 1000 volts, ceramic disk
C11, C19, C20—10 µF, tantalum
C12, C13—not used
C14, C23, C24—1 µF, ceramic
C15—0.001 µF, metal film
C16—39 pF, ceramic disk
C17—120 pF, ceramic disk
C18—0.01 µF, metal film
C21, C22, C31–C47—0.47 µF, ceramic disk
C25–C30—1 µF, tantalum
C48, C49—47 µF, 16 volts, electrolytic

Semiconductors

IC1–IC3, IC9, IC10—LM348 op-amp
IC4—AD625 instrumentation amplifier
IC5—TL431C precision voltage reference
IC6—4051 analog switch
IC7—4052 analog switch
IC8—Altera EP320 PAL
IC14, IC15—OP18012 optoisolator
IC16, IC17—PS2501A optoisolator
IC18, IC20—78L06AC voltage regulator
IC19—78L05AC voltage regulator
D1–D20—1N914 diode
Q1, Q2—IRFD123 N-channel HEXFET

Other components

B1–B3—9-volt battery

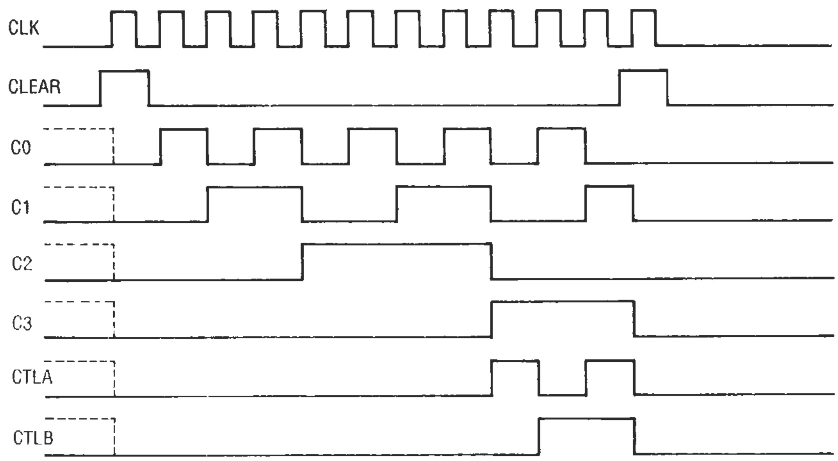


FIG. 6—PAL IC8 SEQUENCES THE MULTIPLEXER ADDRESS LINES so that each input signal is sequentially passed to the multiplexer output for processing. This timing diagram shows the relationships between the PAL's input, output, and control signals.

skilled at reading the ECG without being a medical expert, and there are a number of texts on the subject that you will find interesting. In particular, try Duben's *Rapid Interpretation of EKG's*—with it, you can become fairly knowledgeable of ECG's in a matter of a few hours. A more sophisticated text written by Marriott is entitled *Practical Electrocardiography*. Sources for these texts are listed in the Sources Box of this article.

Biological interface

The patient is connected to the electrocardiogram via 3–12 leads in a typical system. The 3-lead systems are used when only the cardiac rhythm is to be studied—in an ambulance, monitoring an athlete, in an intensive care unit, etc. If a detailed analysis of the heart is required, a 12-channel system is normally used. The system that we will build will generate a full 12-channel read out.

Ten leads are connected to the patient in a 12-channel system: they are right arm, left arm, left leg, and 6 chest leads called the V leads (see Fig. 3). The right leg is used as a ground and as an input to reduce system noise.

You might well ask how we get a 12-channel system only using 9 active leads. That is accomplished by combining different leads together. For example, lead "aVR" is equal to the voltage at the right arm minus the sum of the voltages at the left leg and left arm. Table 1 shows how the signals are combined. Our system will collect the data in each lead, digitize them, and then digitally combine the signals within the host computer. More on this later.

A typical QRS will have a peak amplitude of 1 to 2 millivolts. That may mix with noise (60-Hz hum, for example) with much higher amplitudes. The problem, then, is to distinguish the cardiac signal from the unwanted signal. That is accomplished in biological instrumentation in much the same way as industrial instrumentation: by the use of differential amplifiers. These circuits can attenuate the unwanted signal by 100 dB or more.

The electrode that connects the ECG to the patient must make a low-impedance connection between the system and the patient's skin. That is typically accomplished by the use of disposable silver electrodes, which we will use in our system. The electrodes are made of a silver-chloride gel that provides low impedance and a minimum amount of electrical noise with the skin.

One of the fundamental principles that medicine is based on is from the Hypocrites Oath, "do no harm." That means under no circumstances should there ever be a possibility of doing any harm using medical instrumentation. In the case of an ECG, the main concern would be the shock potential through the electrodes. In our system we optically isolate the patient from the rest of the electronics. Therefore, even if all the safeguards in the computer's power supply were to fail, the patient would still be protected from shock.

One other concern is to prevent the patient from doing harm to our equipment. In our ECG we provide a resistor-diode network on each lead which prevents a high voltage from entering the

ADDRESS FROM PAL				CONTROL FROM PAL		MULTIPLEXER STATE	
						IC 6	IC 7
C3	C2	C1	C0	CTLB	CTLA	IN → OUT	IN → OUT
0	0	0	0	0	0	X0 → X	X0 → X Y0 → Y
0	0	0	1	0	0	X1 → X	X0 → X Y0 → Y
0	0	1	0	0	0	X2 → X	X0 → X Y0 → Y
0	0	1	1	0	0	X3 → X	X0 → X Y0 → Y
0	1	0	0	0	0	X4 → X	X0 → X Y0 → Y
0	1	0	1	0	0	X5 → X	X0 → X Y0 → Y
0	1	1	0	0	0	X6 → X	X0 → X Y0 → Y
0	1	1	1	0	0	X7 → X	X0 → X Y0 → Y
1	0	0	0	0	1	Z	X1 → X Y1 → Y
1	0	0	1	1	0	Z	X2 → X Y2 → Y
1	0	1	0	1	1	Z	X3 → X Y3 → Y

NOTE: Z = OUTPUT IN HIGH IMPEDANCE STATE

FIG. 7—MULTIPLEXER TRUTH TABLE shows how the signals from the PAL are used to control the sequencing of the input signals to the input of the instrumentation amplifier.

front-end amplifiers. An example where this might be significant would be in the case where a patient is "shocked," or defibrillated, after a cardiac arrest. In that case up to 400 volts could appear across the electrodes coming from the patient.

Now that we have a basic understanding of the underlying biological principles associated with the ECG, let's look at some of the technical details of the machine which we will construct. Then let's build one!

System Theory of Operation

A block diagram of the complete ECG system is shown in Fig. 4. The system can be divided into the front-end electronics and the controller. The analog portion attaches to the patient with 10 lead wires; 9 input leads, and 1 output, or reference lead. The analog portion of the ECG is powered by two 9-volt batteries to isolate the patient from any potentially dangerous power circuitry. In addition, data communication between the analog and digital portion of the ECG is accomplished through optical isolators, which also helps keep the patient isolated.

The controller section of the system contains a Z-80 based computer with 32K of RAM and 32K of EPROM. The controller section of the ECG also contains the analog-to-digital (A/D) conversion circuitry to convert the patient's analog ECG signals to the digital data required for computer processing. In addition, this section generates control signals to sequence the A/D conversion, compensate for input channel offset, and control the input-lead multiplexer.

Notice that we have included a personal computer and printer in the diagram. Although not a part of this construction article, they are an integral part of the system since they provide the display for the ECG traces.

Front-end electronics

As previously discussed, the 12-trace ECG is derived from 9 input leads located on the patient. The small (approximately 1 millivolt) signal from each of the leads is fed into the quad op-amps IC1, IC2, and IC3-a, as shown in the schematic of Fig. 5.

The op-amps are configured as non-inverting, unity-gain amplifiers. They provide a very high input impedance that prevents the signals from the body electrodes from being loaded down. Notice also that the input to each amplifier circuit is shunted to ground by a 220-pF capacitor (C1–C10) and two diodes (D1–D20) in parallel. Those components are used to protect the input of the amplifier from the high voltages present during cardiac defibrillation, and to provide patient protection in the unlikely event that high voltage should feed back through the amplifier.

The output of the three limb leads from IC1-a, IC1-b and IC1-c are summed into op-amp IC3-b, inverted, and fed back to the patient through the 10th lead which is attached to the patient's right leg. The composite signal from the three limb leads is called the Wilson Electrode. The Wilson Electrode signal significantly reduces the common-mode noise in the system, since unwanted signals common to the three limb leads are fed back to the patient 180 degrees out of phase with the original noise. The signal from the Wilson Electrode is again inverted in op-amp IC3-c and routed to the multiplexer to eventually form the reference against which the nine input signals are compared.

The multiplexer is made up of two integrated circuits, IC6 and IC7, in conjunction with the multiplexer-controller IC8. Analog-switch IC6 has 8 inputs (X0–X7). One of the eight inputs is connected through a very-low-impedance path to the output (X) according to the 3-bit address appearing on the control inputs C0–C2. For example, X0 is connected to X when the control address is 000, X1 is connected to the output when the control address is 001, and so on. The additional control address C3, is an inhibit which, when high, causes the output X to be a high impedance, effectively turning off the eight input signals to the multiplexer chip. The output of IC6 is routed to one of the inputs to IC7.

Another analog switch, IC7, has 2 outputs and 4 X-Y input pairs (X0–X3 and Y0–Y3). The X0 input is the output from IC6. The corresponding input Y0 comes from the Wilson Electrode, IC3-c. The signal from IC3-a (input 9) is the input to X1. The Wilson Electrode signal is also paired with input 9 on Y1. In addition to the the nine signal inputs from the patient, a 1-mV test signal and a ground input are routed to the X2 and X3 inputs respectively. Ground is the Y2 input for the corresponding 1-mV signal pair as well as for the X3 ground input on Y3.

Two address lines, CTLA and CTLB control which input pair is switched to the outputs. That is, when the control address is 0, inputs X0 and Y0 are switched to outputs X and Y respectively. These control lines as well as the control signals for IC6 are derived from the outputs of IC8.

IC8 is a programmable array logic (PAL) IC which sequences the multiplexer address lines so that each input signal is sequentially passed to the multiplexer output for processing. The PAL is programmed to advance the address on control lines C0 through

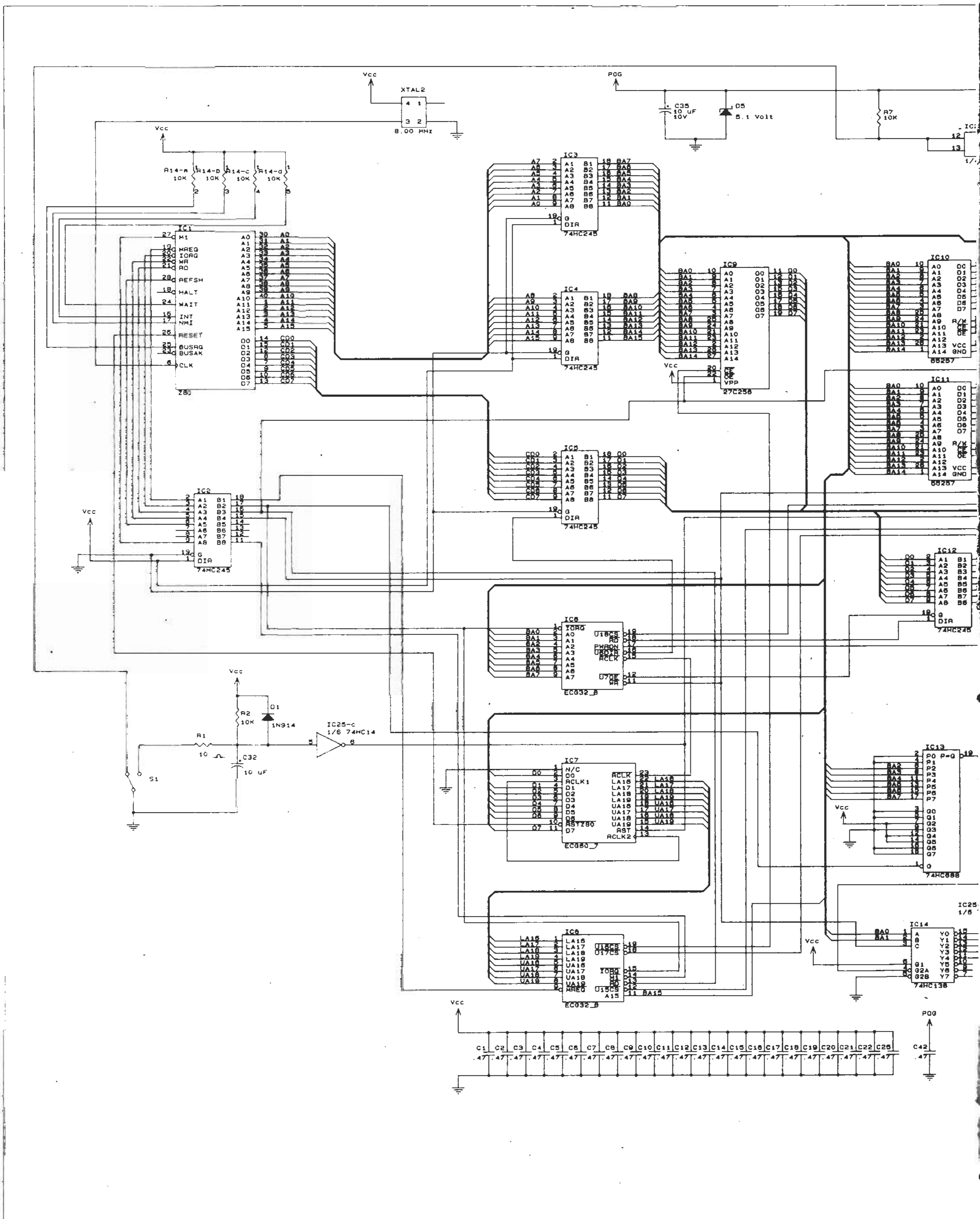
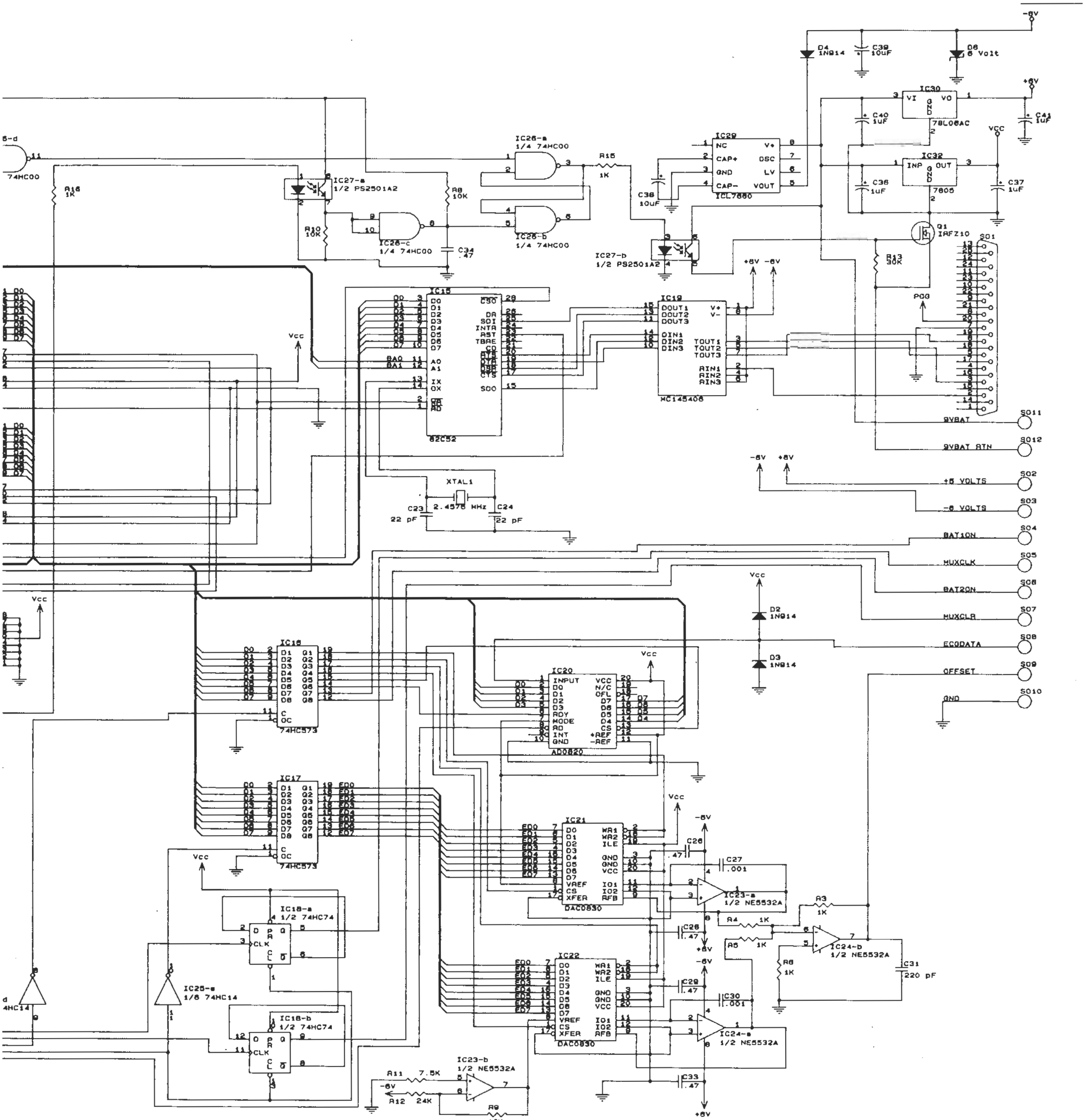


FIG. 8—THE CONTROLLER CONTAINS A Z80-BASED COMPUTER and a digital control section which combine to provide all the sequencing, timing, and control signals for the ECG.



IC27-a 1/2 PS2501A2
IC27-b 1/2 PS2501A2
IC26-a 1/4 74HC00
IC26-b 1/4 74HC00
IC26-c 1/4 74HC00
R15 1K
R16 1K
R8 10K
R10 10K
C34 .47
IC29 ICL7660
NC CAP+ GND CAP- V+ OSC LV VOUT
C38 10uF
D4 1N914
C39 10uF
D6 6 Volt
IC30 78L06AC
C40 1uF
C41 1uF
IC32 7805
C36 1uF
C37 1uF
Q1 IRFZ10
R13 30K
SO1
IC15 82C52
IC19 MC145406
DOUT1 DOUT2 DOUT3 DIN1 DIN2 DIN3 TOUT1 TOUT2 TOUT3 RIN1 RIN2 RIN3
XTAL1 2.4576 MHz
C23 22 pF
C24 22 pF
PGG
9VBAT SO11
9VBAT RTN SO12
+6 VOLTS SO2
-6 VOLTS SO3
BAT1ON SO4
MUXCLK SO5
BAT2ON SO6
MUXCLR SO7
ECGDATA SO8
OFFSET SO9
GND SO10
D2 1N914
D3 1N914
IC16 74HC573
IC17 74HC573
IC20 AD0820
IC21 DAC0830
IC22 DAC0830
IC18-a 1/2 74HC74
IC18-b 1/2 74HC74
IC25-a 1/6 74HC14
IC23-a 1/2 NE5532A
IC23-b 1/2 NE5532A
IC24-a 1/2 NE5532A
IC24-b 1/2 NE5532A
C26 .47
C27 .001
C28 .47
C29 .47
C30 .001
C31 220 pF
C33 .47
R3 1K
R4 1K
R5 1K
R6 1K
R11 7.5K
R12 24K
R9 10K

C3 one count each time a pulse is received on the clock input. Additionally, a decode function is programmed in the PAL to control the state of the control lines CTLA and CTLB and, hence, which signal pairs from the multiplexer are fed to the differential inputs of the instrumentation amplifier. The PAL timing diagram in Fig. 6 shows the timing relationships of the input, output, and control signals from the PAL. The multiplexer truth table in Fig. 7 shows how the signals from the PAL are used to control the sequencing of the input signals to the input of the instrumentation amplifier.

The instrumentation amplifier (IC4 and IC9-b back in Fig. 5) is one of the key signal-processing elements in the ECG design. It is a differential amplifier so its output is equal to the difference between its two inputs multiplied by a gain. In this application, the gain is approximately 1000.

The amplifier also has an input offset adjustment, R12, to compensate for minute differences in the input voltages, as well as an output offset capability at pin 7. In this design, the output offset at pin 7 is biased by IC5, a precision voltage reference, to a constant voltage near 2.5 volts. When the difference between the inputs of the instrumentation amplifier is zero, the output will be 2.5 volts. As the differential input voltage changes from zero, the output of the amplifier will change from 2.5 volts by an amount equal to the input difference times the gain.

The final stage in the analog signal path is the isolation circuitry to the A/D converter. It consists of IC9-a, IC16-c, and IC10-d. As the voltage into IC9-a changes, the current through the LED portion of optoisolator IC16-c changes, which modulates the base of the light-sensitive transistor in the optoisolator. That causes the collector current to change, developing a voltage change across the emitter resistor. That voltage follows the original voltage signal at the input of IC9-a with a 180-degree phase difference. To correct the phase reversal and to compensate for bias and gain errors, the signal is fed through amplifier IC10-d prior to going to the controller board for A/D conversion. In addition to its gain function, IC1-d is also an active low-pass filter, with a cutoff frequency of about 100 Hz.

TABLE 2—CONTROL SIGNAL DEFINITION

Signal	IC16 Output							
	Q8	Q7	Q6	Q5	Q4	Q3	Q2	Q1
Batteries On	1	1	X	X	X	X	X	X
IC21WR	X	X	X	X	X	X	X	0
IC21CS	X	X	X	X	X	X	0	X
IC22WR	X	X	X	X	X	0	X	X
IC22CS	X	X	X	X	0	X	X	X
IC20CS	X	X	X	0	X	X	X	X
IC20RD	X	X	0	X	X	X	X	X

A high pass filter is also implemented in the final stage by feeding the ECG signal from the emitter of IC16-c through an active low-pass filter consisting of IC10-a and its associated components. The cutoff frequency for the low-pass filter is about 0.1 Hz, and the output is fed back through IC16-d to the positive input of IC9-a where it it is used to cancel frequency components of the original signal below 0.1 Hz. As a result, the frequency components of the ECG signal are limited to a band between 0.1 Hz and 100 Hz.

Controller operation

The controller contains a Z80-based computer and a digital control section which combine to provide all the sequencing, timing, and control signals for the ECG (see Fig. 8). The Z80 microprocessor (IC1) is clocked by an 8-MHz oscillator, XTAL2. Octal bus transceivers IC2–IC5 buffer the microprocessor control, address, and data buses, and, in the case of IC5, provide bi-directional capability on the data bus. Programmable logic devices (PLD's) IC6, IC7, and IC8 generate various bus-control and chip-select signals to select the appropriate memory and I/O chips. The 32K × 8 EPROM (IC9) stores the CPU operating system and the ECG control program. Two 32K × 8 static RAM's, IC10 and IC11, provide the CPU with 64K of RAM. Communication with the outside world is provided through a universal asynchronous receiver/transmitter (UART), IC15, and its associated line transceiver IC19.

Power for most of the circuitry on the controller board is provided by a 9-volt battery (B1) located on the front-end board. To extend battery life, the system is powered only during the time required for a single ECG, with each ECG sequence initiated by depressing the reset switch. That is accomplished by powering the start-up circuitry from the RS-232 port on the PC. V_{CC} for the power-on latch, IC26, is provided by the 5-volt Zener-diode regulator, D5.

When the reset switch is depressed, the power-on latch changes state, turning Q1 on and completing the return path for B1. Power for the controller board is provided by the 5-volt regulator, IC32. A +6-volt supply for the analog circuits on the controller board is provided by IC30. The −6-volt supply for the analog circuitry is provided by IC29, a DC-DC converter. The two 6-volt supplies are also used to power portions of the front-end that don't require patient isolation.

The remaining IC's on the controller board are used to generate the control signals and to digitize the ECG data from the nine patient leads. Components IC13 and IC14 decode I/O instructions from the controller to produce control pulses that sequence the acquisition of the ECG data. Table 1 lists the control pulse generated by each I/O port address.

Each time I/O port 52 is addressed, the resulting pulse clocks IC18-a, a D-type flip-flop wired to divide by two. Two outputs to the I/O port produce a single pulse at the output of IC18-a. The pulse is passed to the clock input of IC8 on the front-end board through IC14, an optoisolator also on the front-end board. In a similar manner, a CLEAR pulse is developed at the CLEAR input to IC8 on the front-end board when the controller

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ECG

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addresses I/O port 53. These two pulses control the operation of the ECG signal multiplexer. The other two pulses produced at IC14 when the controller addresses I/O ports 54 and 55 are used to latch data into octal latches IC16 and IC17.

Data latch IC17 stores data for the D/A converters IC21 and IC22. Latch IC16 is used to derive additional control signals.

Table 2 shows that to turn both batteries on and to place the other control signals in an inactive state, all output bits of IC16 must be a 1. To achieve that, the CPU must output 255 to I/O port 54. To subsequently activate, or lower, any of the control bits without disturbing the other bits or turning off the battery power, all bits must be high except for the one corresponding to the activated control signal. After the appropriate bits in IC24 have been activated, the CPU must return them to their inactive state by sending 255 to I/O port 54. The same logic applies to the other signals in Table 2.

To see how this all works together in the circuit, lets assume we need to turn on both the positive and negative battery-powered supplies on the front-end board, and write a 127 to IC21 on the controller board. First, the CPU outputs a 255 to I/O port 54. That places a "1" at all outputs of IC16. The "1" at Q8 of IC16 produces a current flow in the LED of optoisolator IC16-a, causing current to flow through its associated transistor. The ensuing voltage drop across R60 turns FET Q1 on, completing the battery input circuit to the −6-volt regulator, IC11. The negative supply is now on. The positive supplies are turned on by the "1" on Q7 of IC16.

Now the CPU must place our arbitrarily chosen value, 127, into the octal latch, IC17, on the controller board. As shown in Table 1, that is accomplished by writing 127 to I/O port 55. Once the correct number is in the latch, the CPU must write it to the D/A converter. Notice that the outputs of the octal latch, IC17,

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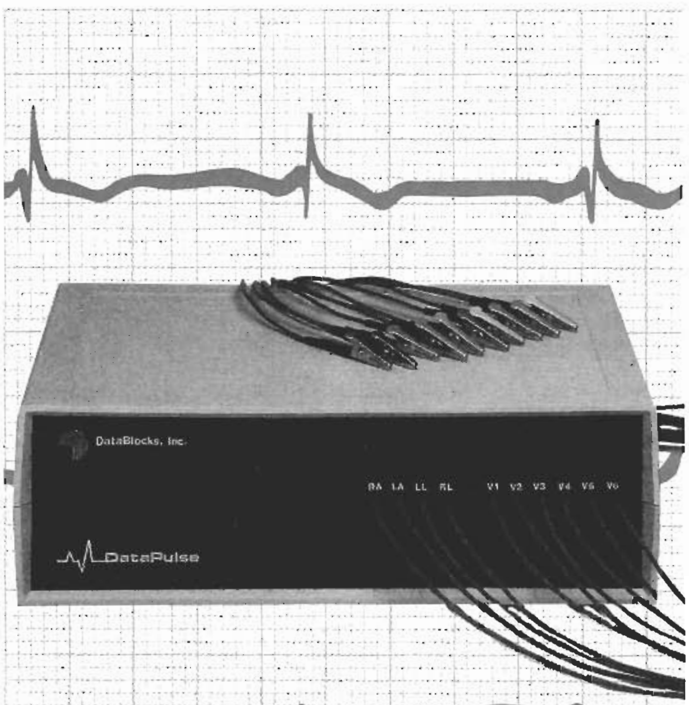
go to both D/A converters, IC21 and IC22. To write the information to IC21 without disturbing the contents of the other D/A converter, the CPU must output a 252 to I/O port 54 to lower Q1 and Q2 of IC16, followed by a 255 to I/O port 54 to return the control signals to their inactive state.

The function of the D/A converters in the circuit are to provide a DC offset to the analog input circuitry to compensate for the DC offset produced by each ECG electrode on the patient's skin. Since the offset, in general, is different for each input lead each time the system is connected to a patient, a means to measure the offset must be provided. That is accomplished by performing a series of calibration measurements just prior to making the ECG measurements.

Next time we will continue with the construction and operation of the ECG device. **R-E**

ELECTROCARDIOGRAPH



Keep an eye on your health and learn about medical electronics with the Radio-Electronics electrocardiograph.

H. EDWARD ROBERTS, M.D.

WARNING!! This article deals with and involves subject matter and the use of materials and substances that may be hazardous to health and life. Do not attempt to implement or use the information contained herein unless you are experienced and skilled with respect to such subject matter, materials and substances.

Furthermore, the information contained in this article is being provided solely to readers for educational purposes. Nothing contained herein suggests that the monitoring system described herein can be or should be used by the assembler or anyone else in place of or as an adjunct to professional medical treatment or advice. Neither the publisher nor the author make any representations as for the completeness or the accuracy of the information contained herein and disclaim any liability for damages or injuries, whether caused by or arising from the lack of completeness, inaccuracies of the information, misinterpretations of the directions, misapplication of the information or otherwise.

LAST MONTH WE DISCUSSED THE OPERATION OF THE CIRcuitry for our electrocardiograph, or ECG. This month we'll build the unit and explain how to use it.

ECG construction

The ECG is relatively simple to build. Double-sided plated-through, silk screened, and solder masked PC boards, as well as all of the necessary components, are available from the supplier listed in the sources box. Software for checkout, data-acquisition, and display are also available. However, we are providing foil patterns so you can make your own PC boards, and we'll post the software on the RE-BBS (516-293-2283, 1200/2400, 8N1) as ECG.ARC.

Mount the components according to the parts-placement diagrams—Fig. 1 for the controller board and Fig. 2 for the front-end board. Most of the IC's are CMOS, and must be handled accordingly. A grounded work bench and soldering iron are strongly recommended, and a static wrist strap is also a good idea. We also recommend you use IC sockets for all the IC's.

Install the IC sockets first, making sure they are flush with the PC board. Then solder in the remaining components on both boards. Make sure the polarized components are properly oriented before you solder them. Inspect the finished boards thoroughly before beginning the system checkout. Do not insert the IC's in their sockets just yet, and don't wire the two boards together until instructed to do so. The finished controller board is shown in Fig. 3 and the finished front-end board is shown in Fig. 4.

Checkout

Begin the system checkout by attaching an RS-232 cable between your PC and the DB25 connector on the controller board. The cable should be wired as shown in Fig. 5 if your PC has a 9-pin communications port, or as shown in Fig. 6 if your PC has a 25-pin communications port. Apply power to the PC and measure the voltage at pins 1 and 8 of IC19. Pin 1 should read about +12V and pin 8 about −12V. Also, check pin 14 of IC26 for 5 volts. If those voltages are correct, install the IC's in the controller board and proceed with the checkout.

Install an unused battery in the B3 battery clip and insert the battery in the holder. Press the reset button on the controller board and measure the output of voltage-regulator IC32 at pin 3. If the output is about 5 volts, the power-on circuitry is working. Remove the battery from the circuit.

The remainder of the checkout will be accomplished by running a checkout program that provides a step-by-step procedure to verify each section of the controller and the front end. Some of the checkout software resides in the ECG program EPROM, IC9, on the controller board. The remainder of the checkout software runs on your PC. When the checkout process is complete, install the two boards in the case and prepare to take your first ECG.

Take an ECG

Skin electrodes with a conductive adhesive back-

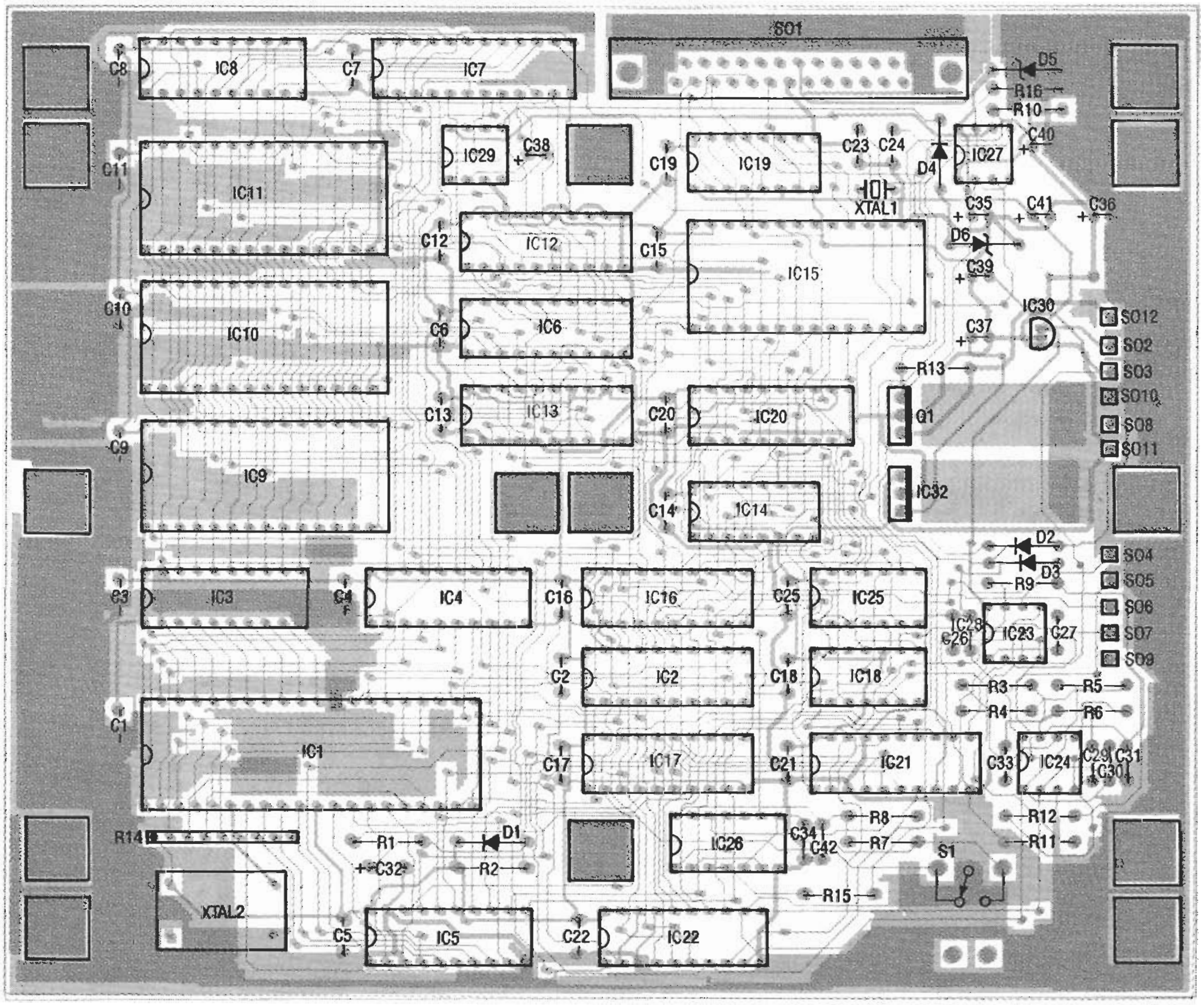
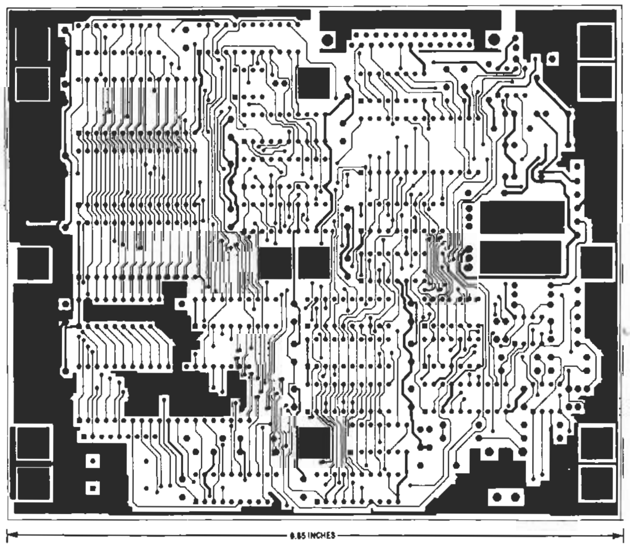
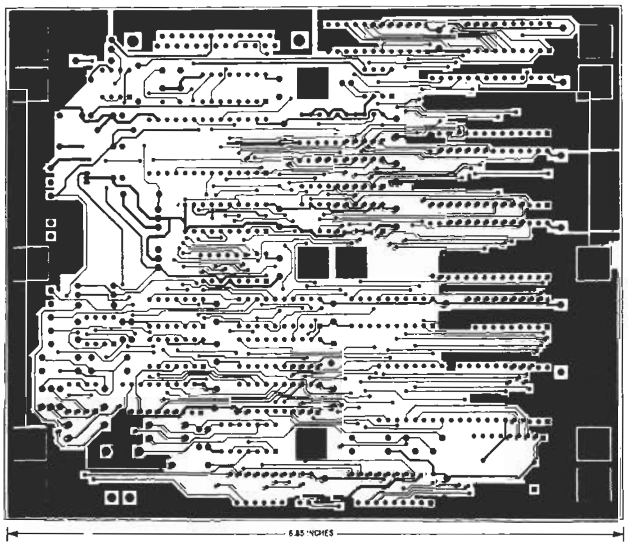


FIG. 1—**MOUNT THE COMPONENTS** for the controller board as shown here, and use IC sockets for all the IC's to reduce the risk of component damage during assembly.

ing are recommended to attach the leads from the ECG to the body. The electrodes are available from the source listed in the sources box. Stick one electrode on each wrist and ankle and at each of the six torso locations shown last month in Fig. 3. Use alcohol to clean the area where

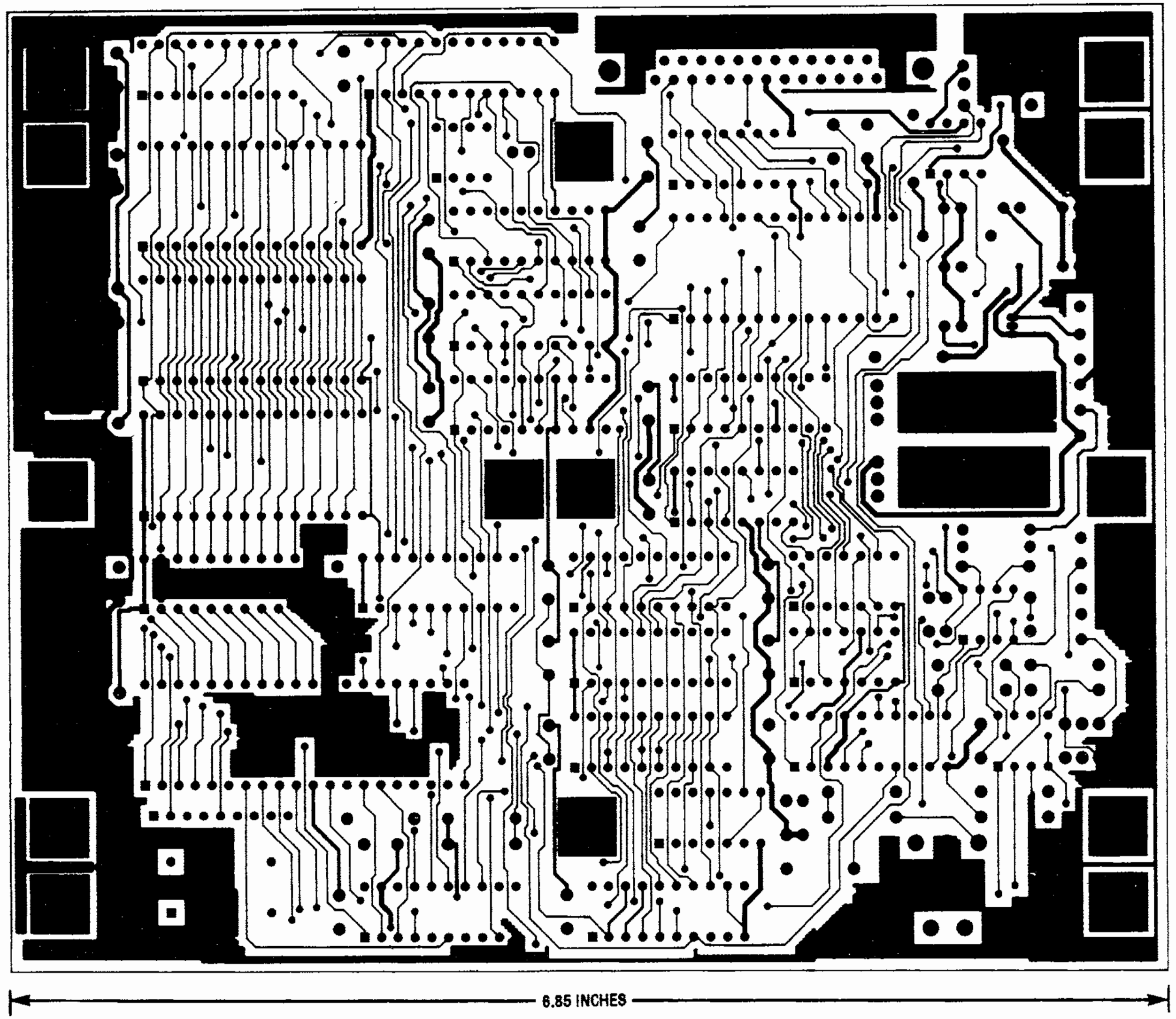


COMPONENT SIDE of the controller board.

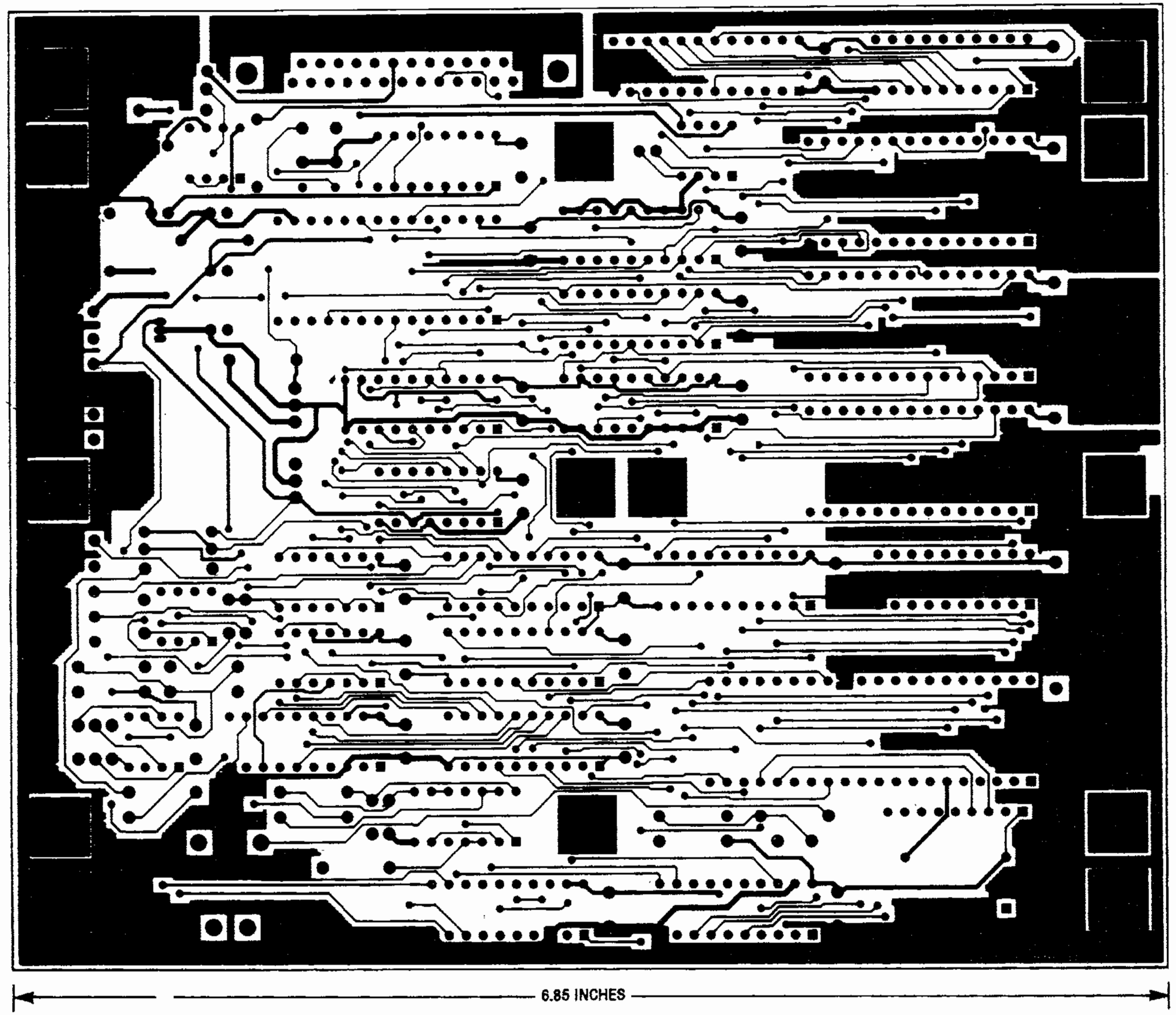


SOLDER SIDE of the controller board.

body. The electrodes are available on each wrist and ankle



COMPONENT SIDE of the controller board.



SOLDER SIDE of the controller board.

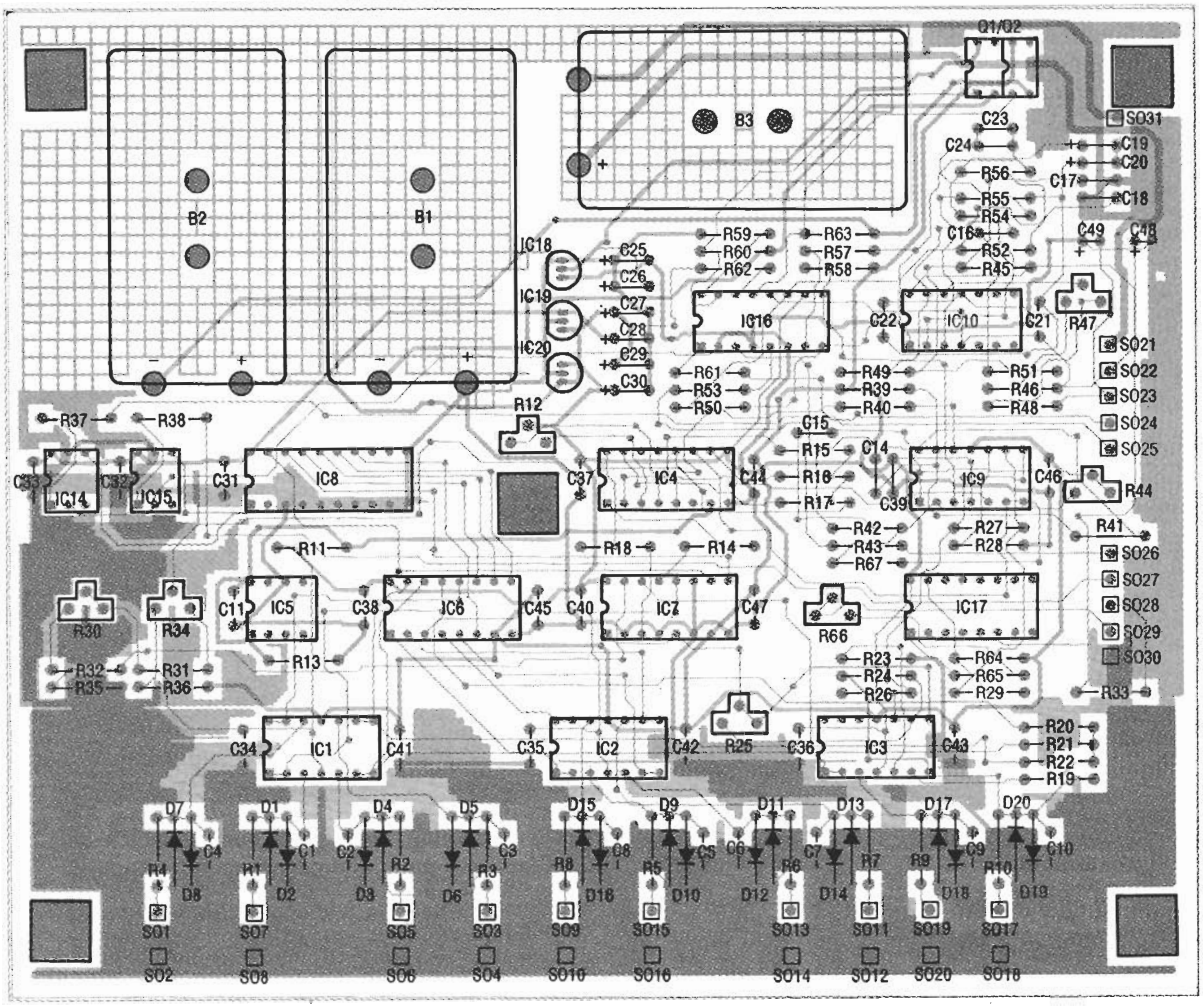
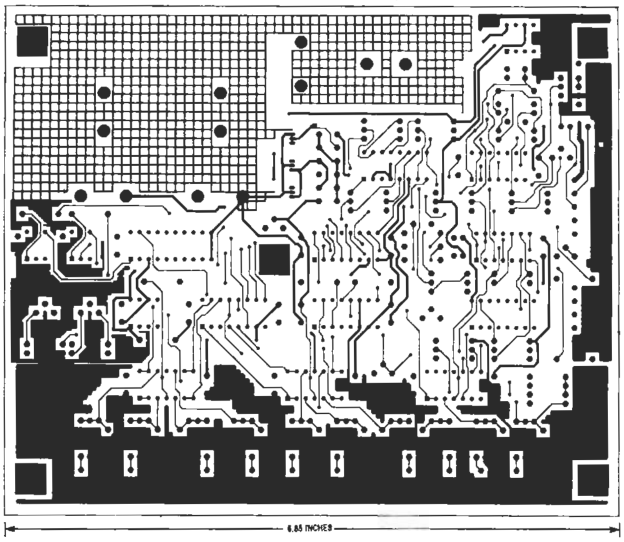


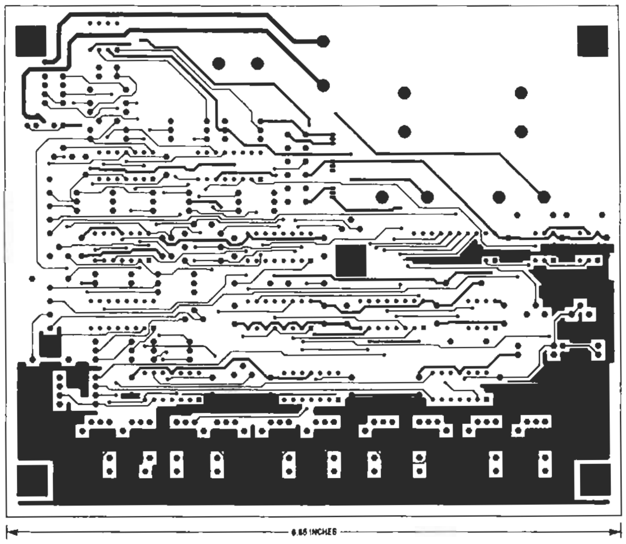
FIG. 2—MOUNT THE COMPONENTS for the front-end board as shown here. Most of the IC's are CMOS, so care must be used in handling them.

the adhesive electrodes will be placed to improve the connection and the signal, and place the electrode in an area with minimal body hair. Using the alligator clips, attach the appropriate lead to each skin electrode.

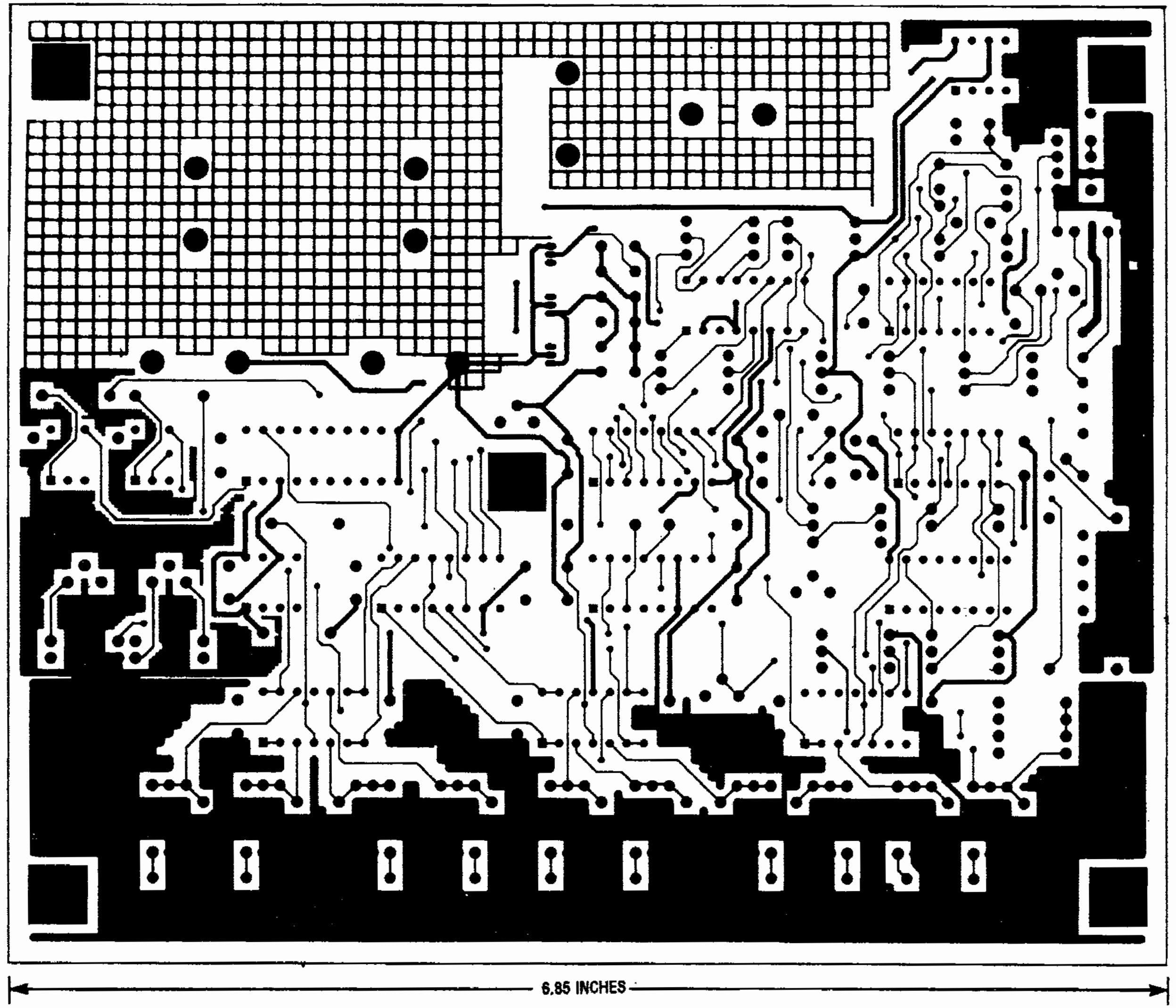
To acquire the ECG, make sure the ECG controller and your PC



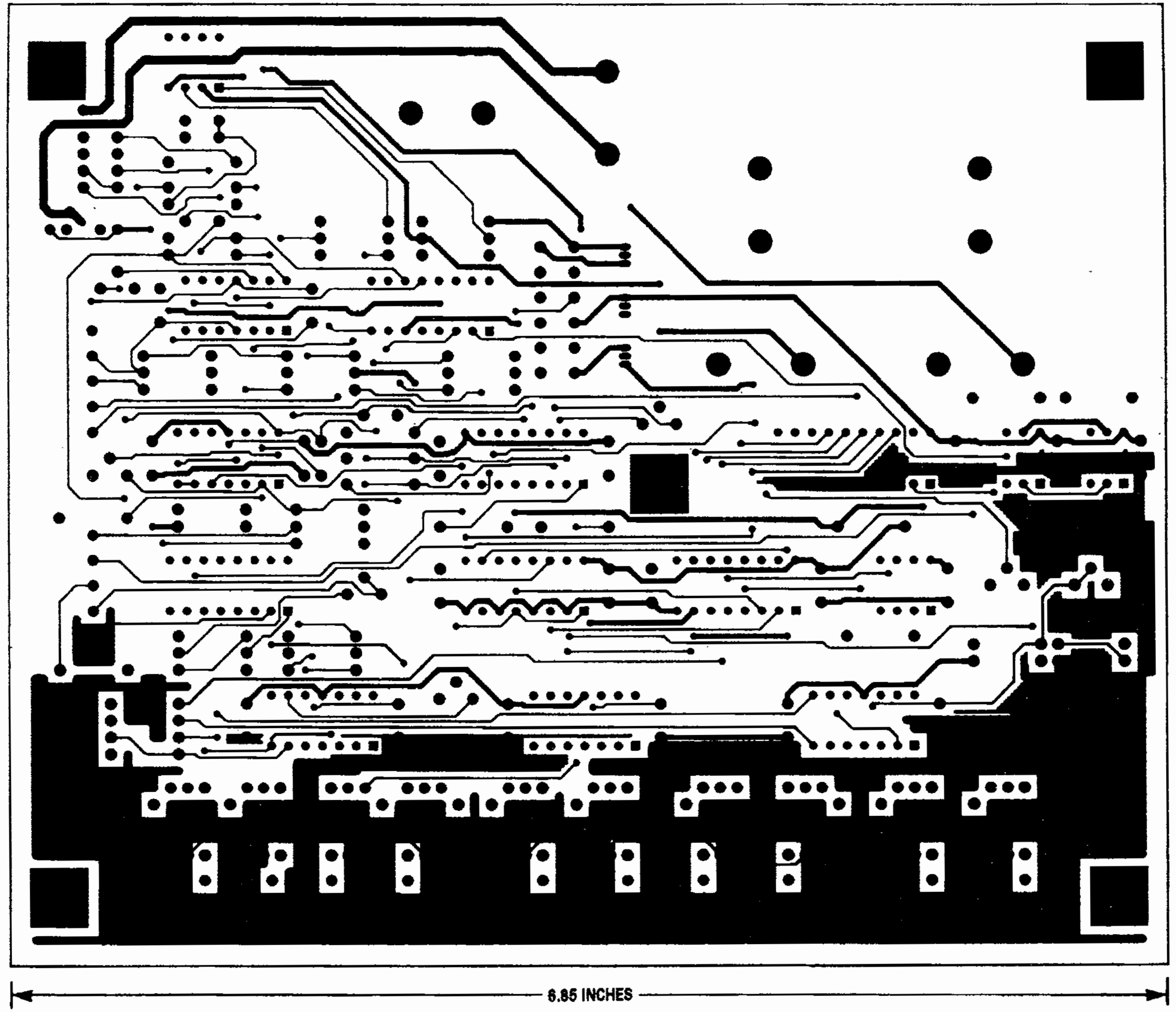
COMPONENT SIDE of the front-end board.



SOLDER SIDE of the front-end board.



COMPONENT SIDE of the front-end board.



SOLDER SIDE of the front-end board.

PARTS LIST—FRONT-END

All resistors are ¼-watt, 5%, unless otherwise noted.
R1–R9, R13—20,000 ohms
R10, R24, R60, R63—30,000 ohms
R11—1800 ohms
R12, R25, R44—10,000 ohms, potentiometer
R14, R18, R26—4700 ohms
R15, R17—19,200 ohms
R16—39.2 ohms, 1%
R19—200,000 ohms
R20–R22, R41—100 ohms
R23—1500 ohms
R27—910 ohms
R28, R39, R40, R43, R55, R59, R62, R67—10,000 ohms
R29, R46, R48—15,000 ohms
R30—200,000 ohms, potentiometer
R31, R36—680,000 ohms, 1%
R32—500,000 ohms
R33—68 ohms
R34—15,000 ohms, potentiometer
R35—100 ohms
R37, R38, R43, R61—470 ohms
R42, R64—1000 ohms
R45, R51—680,000 ohms
R47—5000 ohms, potentiometer
R49—330,000 ohms
R50, R58—2200 ohms
R52, R56—1.5 megohm
R53—150 ohms
R54—150,000 ohms
R57—12,200 ohms
R65—3300 ohms
R66—1000 ohms, potentiometer

Capacitors
C1–C10—220 pF, 1000 volts, ceramic disk
C11, C19, C20—10 µF, tantalum
C12, C13—not used
C14, C23, C24—1 µF, ceramic
C15—0.001 µF, metal film
C16—39 pF, ceramic disk
C17—120 pF, ceramic disk
C18—0.01 µF, metal film
C21, C22, C31–C47—0.47 µF, ceramic disk
C25–C30—1 µF, tantalum
C48, C49—47 µF, 16 volts, electrolytic

Semiconductors
IC1–IC3, IC9, IC10—LM348 op-amp
IC4—AD625 instrumentation amplifier
IC5—TL431C precision voltage reference
IC6—4051 analog switch
IC7—4052 analog switch
IC8—Altera EP320 PAL
IC14, IC15—OP18012 optoisolator
IC16, IC17—PS2501A optoisolator
IC18, IC20—78L06AC voltage regulator
IC19—78L05AC voltage regulator
D1–D20—1N914 diode
Q1, Q2—IRFD123 N-channel HEXFET

Other components
B1–B3—9-volt battery

ORDERING INFORMATION

Note: The following items are available from DataBlocks, Inc., Glenwood, GA 30428, (912) 568-7101.

- **Design package including schematics, assembly instructions, and checkout- and plot-software design specifications (ECG-DP): $27.00.**
- **Front-end PC board, controller PC board, and design package from above (ECG-PC): $74.00.**
- **Complete kit of parts, including both PC boards, IC's, sockets, passive components, design package, ECG software, and checkout software (ECG-KIT): $289.00.**
- **Lead kit consisting of 50 feet of 29-gauge shielded cable, 10 alligator clips, heat-shrink tubing, and instructions (ECG-LD): $53.00.**
- **EPROM containing ECG software, ECG resident portion of checkout software (ECG-PROG): $45.00.**
- **Set of four programmed PAL's (ECG-PAL): $67.00.**
- **Case as shown with mounting hardware (ECG-CASE): $29.00.**
- **Package of 100 self-adhesive electrodes (ECG-EL): $20.00.**

Please include $5.00 shipping and handling for design package and electrodes, $10.00 shipping and handling for all other products. Georgia residents must add sales tax.

PARTS LIST—CONTROLLER BOARD

All resistors are ¼-watt, 5%, unless otherwise noted.
R1—10 ohms
R2, R7–R10—10,000 ohms
R3–R6, R15, R16—1000 ohms
R11—7500 ohms
R12—24,000 ohms
R13—30,000 ohms
R14—10,000 ohms × 8, SIP

Capacitors
C1–C22, C25, C26, C28, C29, C33, C34, C42—0.47 µF, ceramic disk
C23, C24—22 pF, ceramic disk
C27, C30—0.001 µF, metal film
C31—220 pF, ceramic disk
C32—10 µF, 10 volts, electrolytic
C35, C38, C39—10 µF, 10 volts, tantalum
C36, C37, C40, C41—1 µF, 10 volts, tantalum

Semiconductors
IC1—Z80 CPU
IC2–IC5, IC12—74HC245 bus transceiver
IC6, IC8—Altera EP320 PAL
IC7—Altera EP600 PAL
IC9—27C256 EPROM
IC10, IC11—55257 static RAM
IC13—74HC688 equality comparator
IC14—74HC138 1-of-8 decoder
IC15—82C52 UART
IC16, IC17—74HC573 octal latch
IC18—74HC74 dual D flip-flop
IC19—MC145406 RS232 transceiver
IC20—AD0829 A/D converter
IC21, IC22—DAC0830 D/A converter
IC23, IC24—NE5532A op-amp
IC25—74HC14 hex Schmitt inverter
IC26—74HC00 quad NAND gate
IC27—PS2501A-2 optoisolator
IC28, IC31—not used
IC29—ICL7660 DC-DC converter
IC30—78L06AC voltage regulator
IC32—7805 voltage regulator
D1–D4—1N914 diode
D5—5.1-volt Zener diode
D6—6-volt Zener diode
Q1—IRFZ10 N-channel MOSFET

Other components
XTAL1—2.4576 MHz crystal
XTAL2—8.00 MHz oscillator
S1—SPDT momentary contact switch
SO1—DB25 connector

are connected with the RS232 cable used when you checked out the system. Load and run the data collection batch file, ECG.BAT, in your PC. Input the patient information that the program requests, terminating each answer with a carriage return. After the last response, press the reset button on the ECG to initiate data collection. Make sure the patient does not move during the collection process.

You will see a message on the PC as soon as the data collection process starts. After about 30 seconds you will see a message on the PC indicating that data is being transferred between the ECG and the PC. That is an indication that the ECG has finished collecting data. After the data has been transferred, your PC will begin processing it for display. Depending upon the speed of your PC, the graphs of the ECG will appear after a few seconds of processing. In addition to the plots shown on the CRT, each of the plots may be sent to your dot-matrix printer for a permanent record.

Now let's examine the hardware and software interactions involved with taking the ECG you just finished. First, assume the RS232 ports between the ECG and the PC have been connected, the PC has been booted, and the ECG batch file run. As soon as the ECG reset button is pressed, the microprocessor in the ECG controller boots up and enters a wait loop, waiting for the PC to announce to the ECG that it is time to begin taking data. After the initialization prompts for patient information, and the name of the file that will be used to store the ECG data has been entered through the PC keyboard, the PC

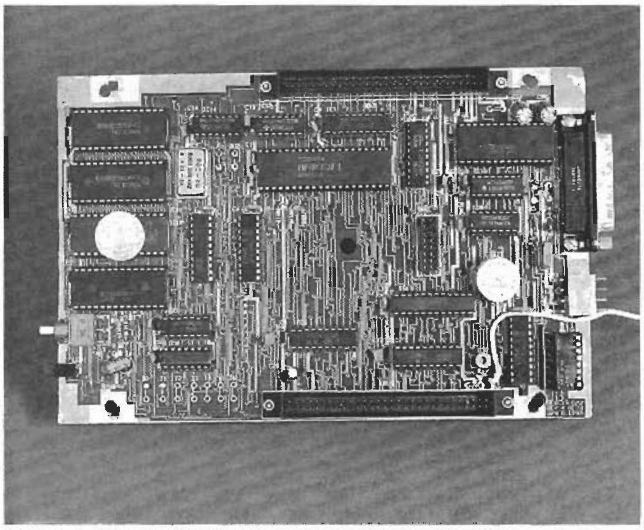


FIG. 3—THE FINISHED CONTROLLER BOARD will look similar to this one, although this is an early prototype board. Inspect the finished boards thoroughly before beginning the system check-out.

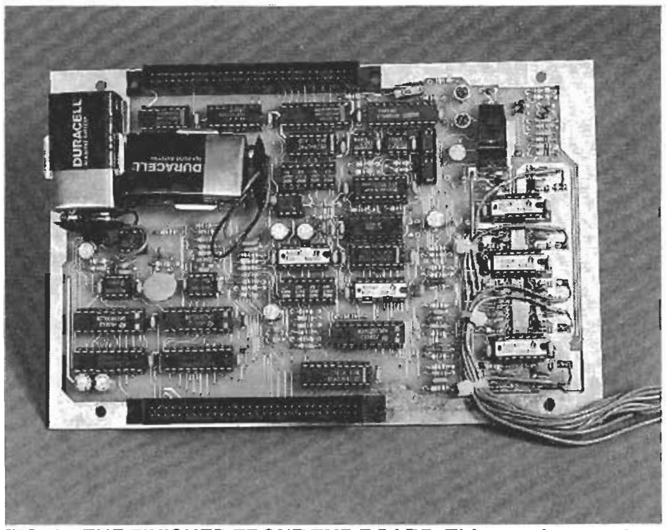


FIG. 4—THE FINISHED FRONT-END BOARD. This, too, is an early prototype, so your board won't look exactly like this one. Do not wire the two boards together until you are told to do so.

software transmits a control character to the ECG that causes it to start the ECG data-collection process.

The ECG turns both batteries on and enters a calibration routine. The first part of the routine determines whether the batteries are charged. That is accomplished by digitizing the output of IC10-d in the front-end electronics with the differential inputs to the instrumentation amplifier, both connected to ground through IC7. If the batteries are good, the voltage measured will be the 2.5-volt offset from the differential amplifier. If both batteries are not fully charged, the voltage from the divider formed from R31, R34, and R36 will change, causing the output of IC10-d to change from the expected 2.5 volts. If the batteries are not good, the ECG outputs a "low battery" message to the PC and stops. If the batteries are good, the channel calibration routine is entered.

The channel calibration routine determines the appropriate channel offset for each of the nine input channels. That is accomplished by sequentially connecting each of the input channels to the positive input of the differential amplifier and comparing its voltage to that of the Wilson electrode connected to the negative input of the differential amplifier. If those two voltages are equal, the digitized output of the differential amplifier will be its offset voltage, 2.5 volts. If the input lead is not equal to the Wilson electrode, a bias is added to the channel by incrementing the output of either IC21 or IC22 in the appropriate direction; IC21 is used for coarse changes, while IC22 is used for smaller increments. That change is added to the output of the other D/A converter at the summing junction of IC24-b and passed to the front-end board.

On the front-end board, the change goes through the optical isolator IC17-a and op-amp IC9-c to the summing junction of IC3-c, where it adds with the input channel being measured. After an appropriate delay to let the voltages in the loop settle, the output of the differential amplifier is sampled again. The process is continued until the difference between the input channel and the Wilson electrode voltage is within acceptable limits, at which time the system sequences to the next channel. The digital values required to adjust the analog output of IC21 and IC22 to bring the channel biases within acceptable limits are stored in the software to be used during the data-acquisition process.

The data-acquisition routine is entered immediately after the last channel bias has been determined. This routine digitizes the difference between each input lead and the Wilson electrode, in sequence, and stores the sample in memory. Prior to digitizing the sample, the channel bias values for the channel being sampled, determined during the calibration sequence, are retrieved from the software and placed in the D/A converters, as previously described. Each channel is sampled as rapidly as the processing and loop settling time will permit. The software then enters a wait period before sampling the next data set to achieve a 400-sample-per-second rate on each of the nine channels. Two thousand samples are obtained from each channel and placed in memory for subsequent transfer to the PC for display.

At the completion of the data-acquisition phase, the ECG controller turns the batteries B1 and B2 off and signals the PC that the data is available for transfer. When the PC detects that it acknowledges the message and starts its transfer routine. The ECG also sets up a transfer routine and the data is passed from the ECG to the PC. At the conclusion of the transfer, the ECG powers itself down, waiting for the PC to signal that it is time to acquire another ECG. The PC begins to process the data it just received during the transfer.

The data transferred to the PC must be processed before it can be displayed as one of the twelve standard ECG leads. Remember that the digitized information is the difference between the input channel and the Wilson electrode. The first six ECG leads, however, are combinations of input channels compared with one or more other input channels. For example, consider the standard ECG lead I. This lead is defined as the electrical activity from the heart measured on the left arm with respect to the right arm. Let S1 designate a sample from the right arm with respect to the Wilson electrode, and S2 designate a sample from the left arm with respect to the Wilson electrode. In other words:

$S1 = RA - W$

$S2 = LA - W$

Now,

$I = LA - RA = (S2 + W) - (S1 + W)$

$I = S2 - S1$

so that the PC must subtract Sample 1 from Sample 2 to get lead I. In an analogous manner leads II and III are derived from their definitions as:

$II = S2 - S3$

$III = S1 - S3$

The augmented leads are somewhat more complicated to derive from the samples. Recall that an augmented lead is defined as the electrical activity on one of the three input leads with respect to the other two leads. For example:

$AVR = RA - (LA + LF)$

Now,

$S1 = RA - W$

$S2 = LA - W$

$S3 = LF - W$

so that

$AVR = S1 - S2 - S3 - W$

Recall that W, the Wilson electrode, is the sum of RA, LA and LF ($W = RA + LA + LF$) so that:

$S1 = RA - W = RA - RA - LA - LF = -LA - LF$

$S2 = LA - W = LA - RA - LA - LF = -RA - LF$

$S3 = LF - W = LF - RA - LA - LF = -RA - LA$

Adding the samples:

$S1 + S2 + S3 = -2RA - 2LA - 2LF = -2W$

or

$W = -(S1 + S2 + S3)/2$

and

$AVR = S1 - S2 - S3 - W$

$= S1 - S2 - S3 + (S1 + S2 + S3)/2$

$AVR = S1 + (S1 - S2 - S3)/2$

Using the same arithmetic, it can be shown that

$AVL = S2 + (S2 - S1 - S3)/2$

$AVF = S3 + (S3 - S2 - S1)/2$

The chest leads V1 through V6 are defined as simply the electrical activity on the lead with respect to the Wilson electrode.

The processed data is stored on your disk drive under the file name you entered. In addition, three traces are plotted on the CRT with each trace broken into four parts. The traces are segmented as follows:

Trace 1 = Lead I, AVL, V1, V4
Trace 2 = Lead II, AVR, V2, V5
Trace 3 = Lead III, AVF, V3, V6

You should have enough information now to use the ECG. However, if you're not a doctor, don't think of yourself as one—and be sure to see a medical doctor if you suspect any health problems. **R-E**

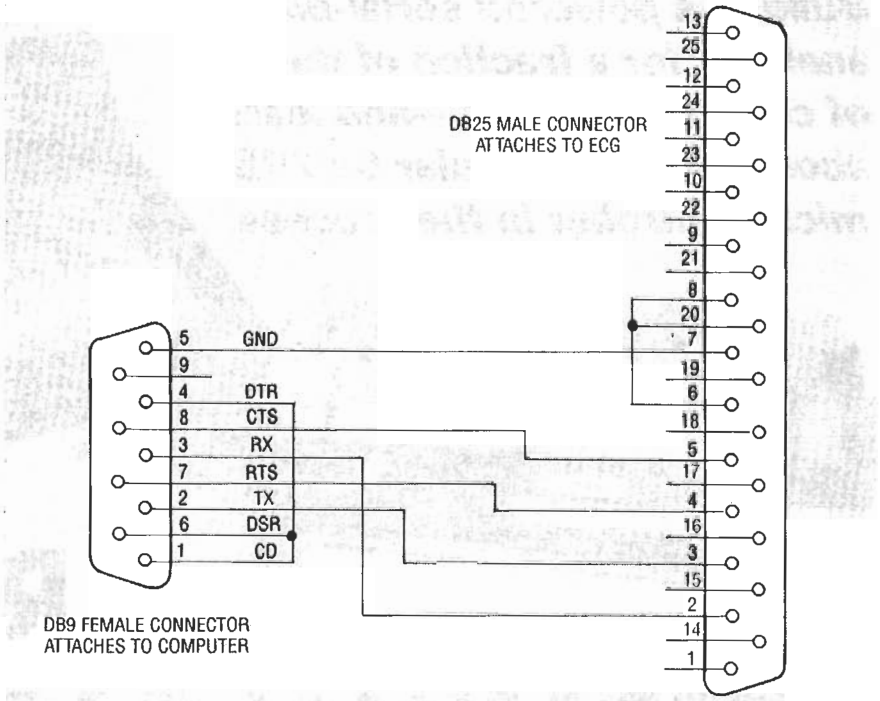


FIG. 5—THE RS232 CABLE between your PC and the DB25 connector should be wired as shown here if your PC has a 9-pin communications port.

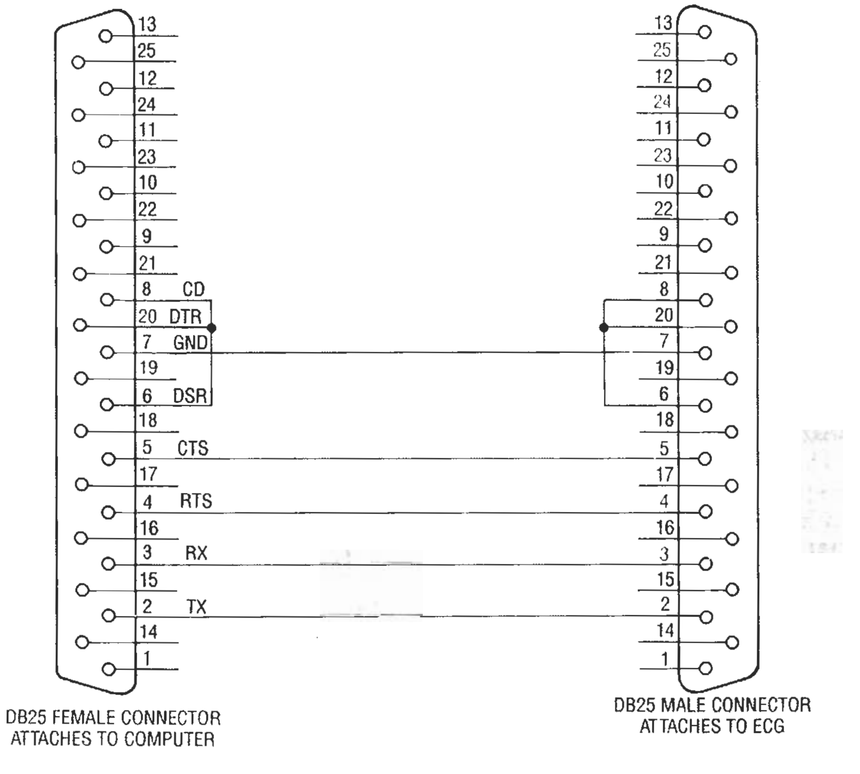


FIG. 6—IF YOUR PC HAS A 25-PIN communications port, wire the the RS232 cable between your PC and the DB25 connector as shown here.