your own little PHOTOPLETHYSMOGRAPH

Unusual project shows heart action and blood flow

Hundreds of times each day, in the leading hospitals of the world, surgeons perform miraculous feats of surgery made possible by daring innovations in technique and an array of the finest equipment money can buy. An important member of the surgical team is the anesthetist. He leans heavily on modern medical electronic instrumentation, and can now keep his full attention on the unconscious form before him while the important heart data is supplied to him aurally. This information comes in the form of a soft rhythmic "bleep" emanating from an electronic monitor. If the *bleep* should falter, the signal can be switched from an audible to a visual presentation. The anesthetist would then be able to study the heartbeat waveform displayed on the face of his small, battery-operated oscilloscope.

This heartbeat signal originates in a photocell transducer that has been slipped over one of the patient's fingers. It has the rather formidable name of photoplethysmograph, usually abbreviated to PPG. The "plethysmo" portion of the word is derived from the Greek "plethore," meaning "to be full." Basically, the transducer measures the blood volume flow in the finger to which it is attached. This is an excellent indication

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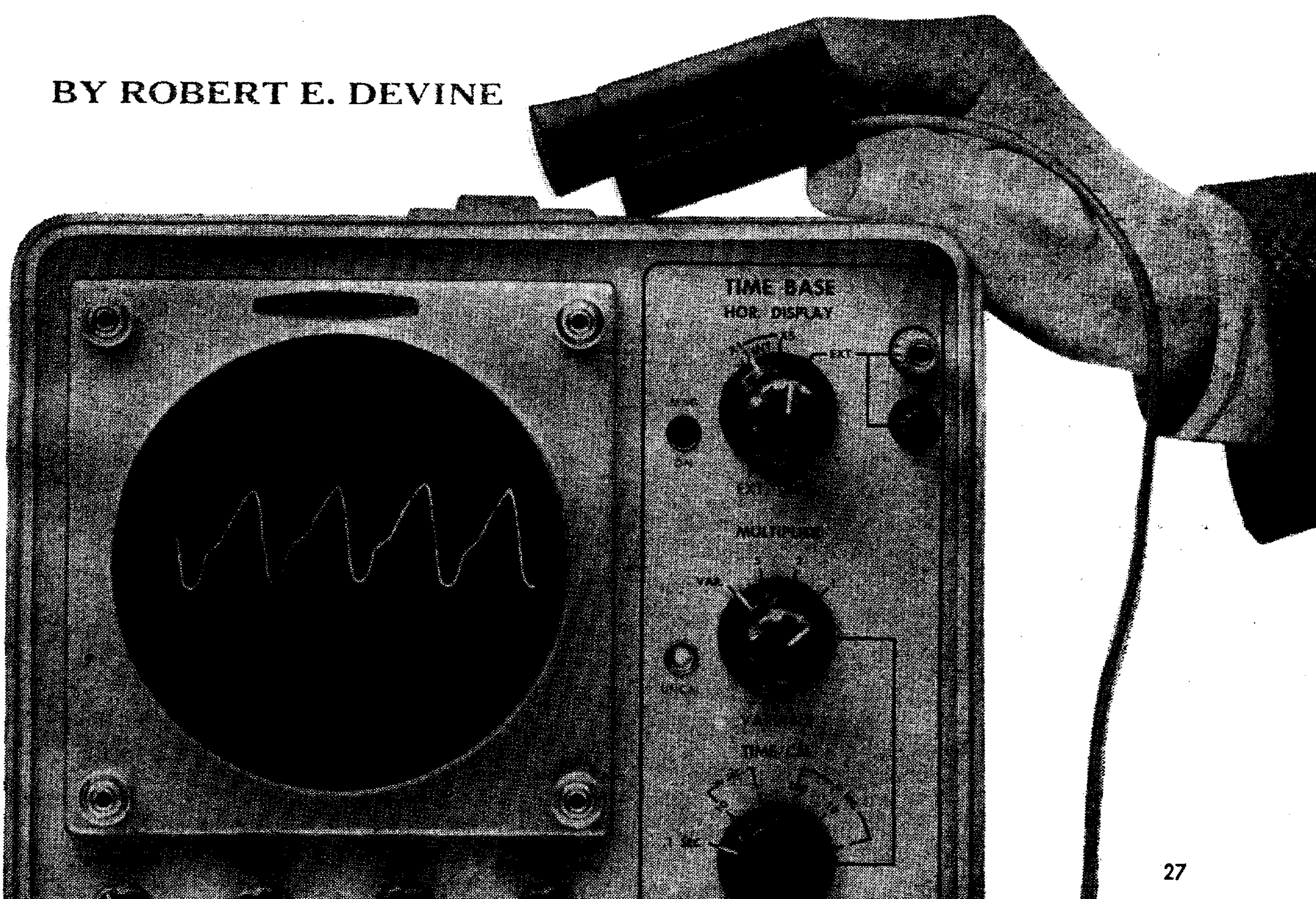


PARTS LIST

B1—22.5-volt battery
B2—1.5-volt battery
I1—Pilot bulb #222, or "grain-of-wheat" bulb
J1—Three contact polarized socket
P1—Three contact polarized plug
PC1—Photocell sensitive to approximately 7350 Angstroms (Clairex CL903L or similar)
R1—5600-ohm, ½-watt resistor
R2, R3—10,000-ohm, ½-watt resistor
S1—D.p.s.t. switch
Misc.—Block of wood or opaque plastic approximately 2½" x 1½" x ½", thin metal plate, battery holders, length of 2-conductor flexible shielded cable with three-pin polarized plug (from transducer to bridge), length of phono cable with two-pin polarized plug (from bridge to preamp or scope), finger support (see text), connector for scope or preamplifier (optional), 25,000-ohm potentiometer (optional, see text), terminal strips, hardware, etc.

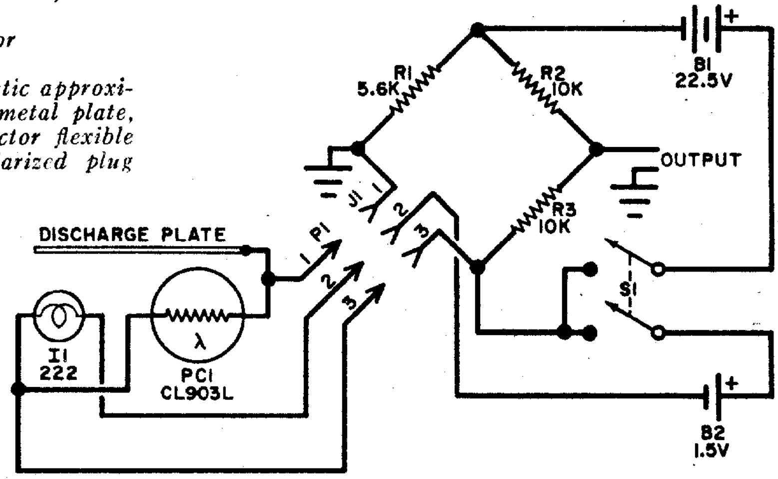


Fig. 1. The PPG circuit is a simple bridge with photocell PC1 as the variable arm. The plate bleeds off static electricity. The shield of the transducer cable is the common ground lead and is connected to pin 1 of P1. The output cable is a shielded single-lead microphone cable.

of how efficiently the heart is working. If the patient's condition warrants it, this pressure pulse monitor will accompany the patient to the recovery room. The PPG is also used in intensive care hospital rooms. Its signal can be carried by cable to a central observation point where it may be monitored continuously by either visual display or an audible signal. The electronic vigil will watch-and-warn for that critical 200 seconds—the period between the instant the heart ceases to pump, and death. The heart must be restarted during this critical interval to save the patient's life.

The actual waveform generated by the pressure pulse has a frequency of only one or two hertz—much too low to be heard by the human ear. In an aural setup this signal triggers an electronic tone generator whose frequency has arbitrarily been selected to be something "easy to listen to." The important information conveyed by the *bleep* is the tempo and regularity of the heartbeat. On the other hand—when the waveform is displayed on an oscilloscope, all the above information, plus other physiologically significant events, can be extracted from a visual observation of the waveform.

If you have a good oscilloscope, you

PARTS LIST

B1—22.5-volt battery
C1—12-μF, 20-volt tantalum capacitor
C2—75-μF, 6-volt electrolytic capacitor
J1—Two contact polarized socket
Q1—N-channel FET (Motorola MPF103 or similar)
R1, R4—2-megohm
R2—470-ohm
R3—7500-ohm
} *all resistors ½-watt*
S1—S.p.s.t. switch
S2—S.p.s.t. momentary contact switch
Misc.—Metal case 4" x 2¼" x 2¼", transistor socket, battery holder, length of shielded flexible cable (from amplifier to scope), terminal strips, hardware, etc.

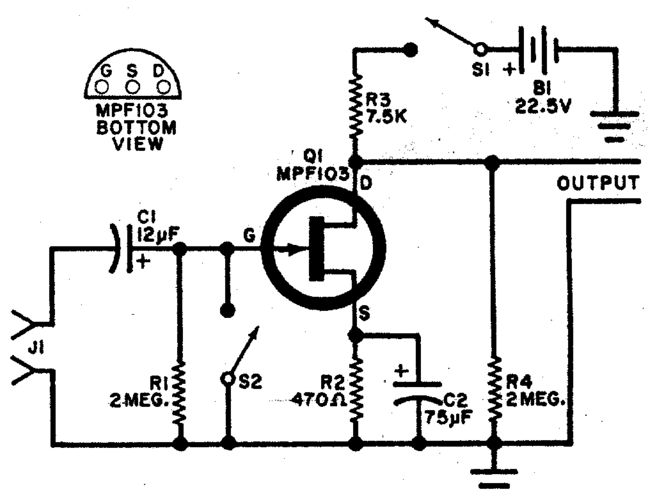
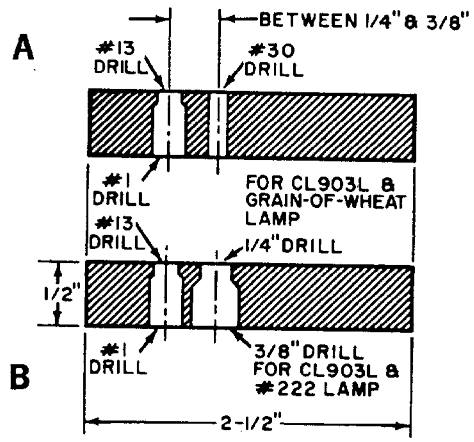


Fig. 2. Output level of the bridge is very low and this special preamplifier may be required. Capacitor *C1* is made of tantalum foil.



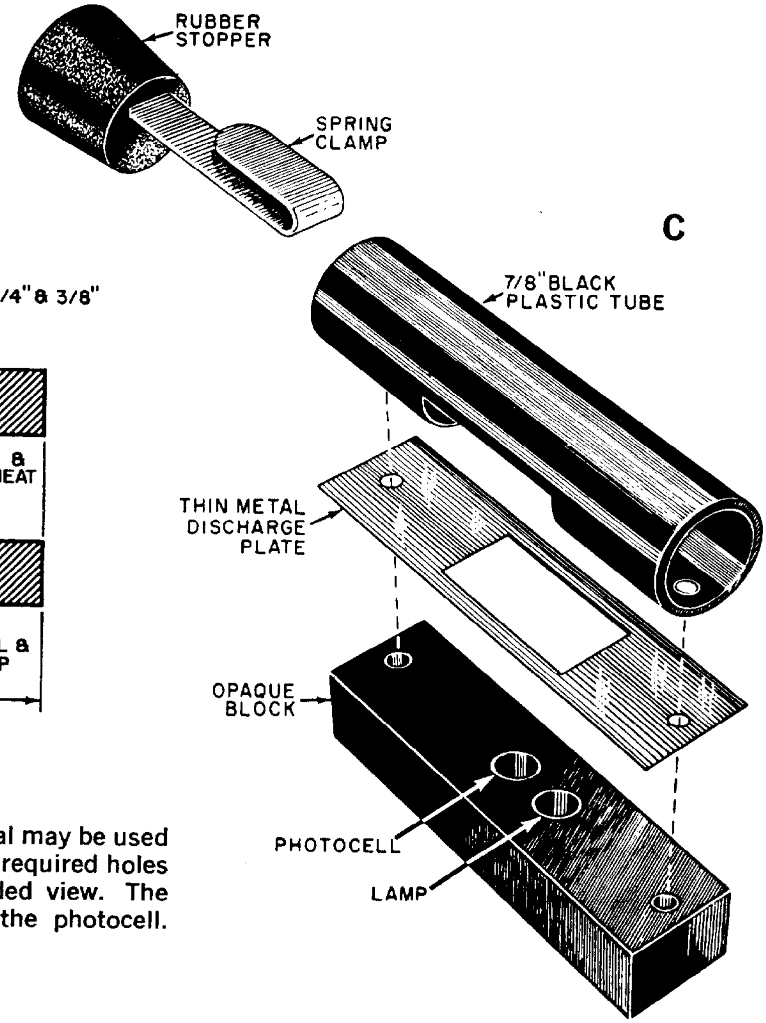


Fig. 3 Any workable opaque material may be used to make the transducer body. Drill required holes and assemble as shown in exploded view. The discharge plate is connected to the photocell.

can reduce the cost of building your own PPG to approximately six dollars. Construction time should be just a few hours.

Construction. The PPG is divided into three cable-connected sections: the finger-mounted transducer assembly, the measuring bridge, and a FET signal preamplifier (optional). The circuit for the transducer and bridge is shown in Fig. 1 and the schematic for the FET preamplifier is shown in Fig. 2.

To make a transducer, a piece of opaque plastic or wood approximately 2½" x 1½" x ½" is drilled to accept the photocell and lamp as shown in Fig. 3. There are two methods of drilling the holes for the light source. Fig. 3(a) shows the drilling requirements for a grain-of-wheat lamp, while Fig. 3(b) shows the drilling for a #222 lamp. In both cases, the hole for the photocell remains the same size. Each unit should be submerged within the opaque block so that they do not "see" each other unless

HOW IT WORKS

The PPG takes advantage of the fact that tissues of the human body are relatively transparent to the red part of the light spectrum (near infrared region from 7000 to 8000 Angstroms), while the blood is not.

When you place your finger across the gap separating the reddish light source and the photocell, your flesh will provide a path for the light rays to reach the photocell from light source. With each systole, or contraction of the heart muscles, the amount of blood in your peripheral extremities increases as the blood vessels momentarily dilate. Since blood is opaque to the red light, this reduces the amount of light reaching the photocell during the pressure pulses. The change in light causes the photocell to change its resistance with each pulse.

The photocell is connected in a bridge circuit (see Fig. 1) with *R1* being its opposite bridge element. Equal value resistors *R2* and *R3* provide a mid-point pickoff for the output signal. Each time the photoresistor changes its resistance value, an output signal is generated by the bridge.

Because the bridge output is a low-level, low-frequency signal, the FET preamplifier shown in Fig. 2 may be used to increase the signal level to a point usable by some scopes. This preamplifier is a conventional FET stage having the required very high input impedance so as not to reduce the low-frequency coupling *(C1)* at these one-to-two-Hz subaudible frequencies.

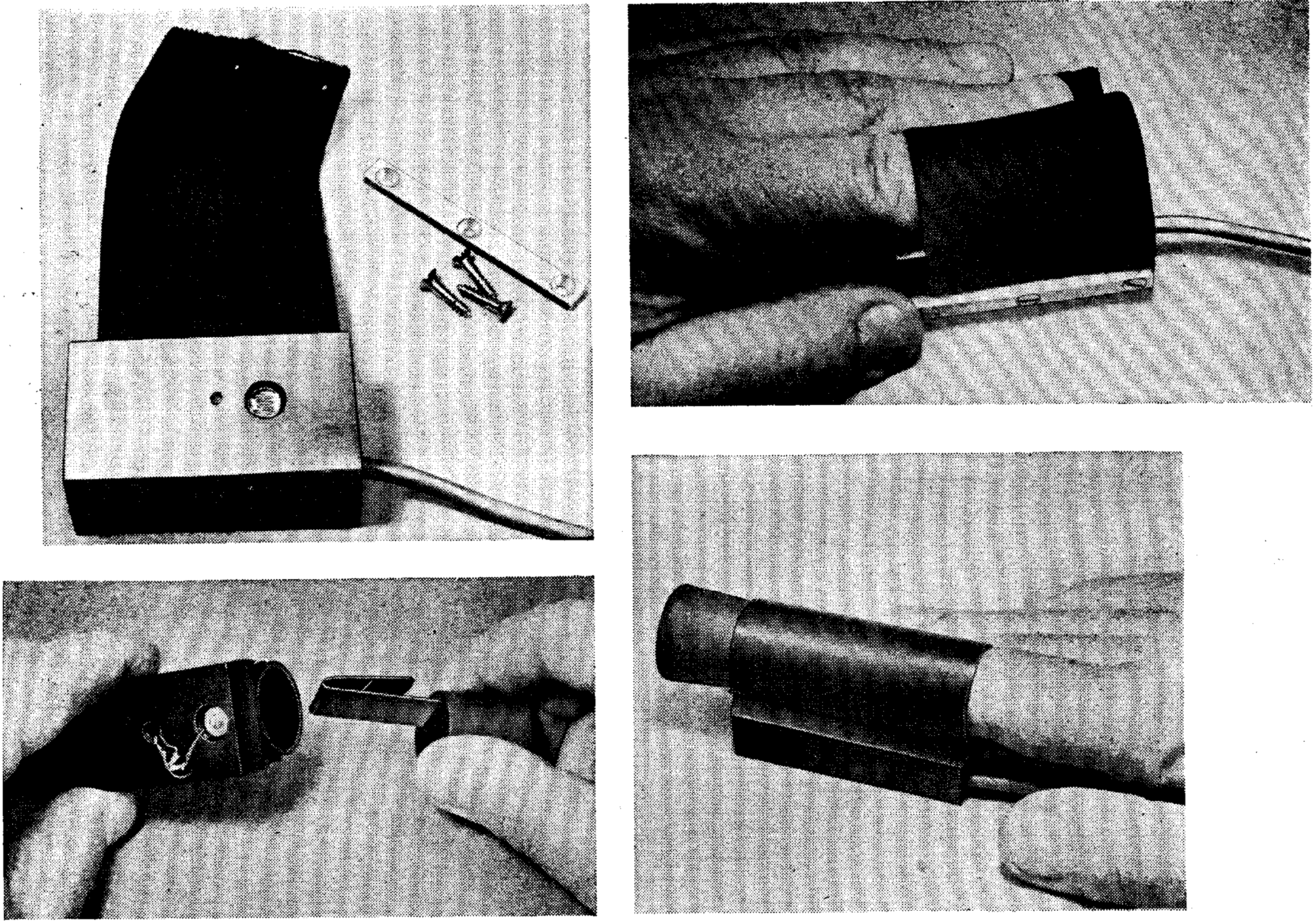


Fig. 4. Two preferred methods of assembling a transducer are shown. In the upper two photos, an elastic cloth has been used to secure the finger and block off outside light. The photocell and light source are visible through the holes in the metal plate. The two lower photos show tube transducer.

a finger is so placed as to make a reflective bridge between photocell and lamp.

To remove any static electricity charge, a thin metal plate covers the top of the opaque block with a cutout over the lamp and photocell holes. This is shown in Fig. 3(c). The metal plate is connected to the ground lead of the transducer-bridge cable.

A light shield surrounding the finger and the photocell is recommended. Use a black (opaque) plastic tube that can be bolted to the opaque block, with a cutout as shown in Fig. 3(c). To make sure that the finger correctly bridges the *I1-PC1* gap, make up a clamp using a rubber stopper and a home-made spring. The stopper should be a tight fit in the end of the plastic tube. The spring clamp is inserted so that when a finger is placed in the tube (fingernail up), the clamp will force the finger down to bridge the *I1-PC1* gap. An alternative construction method is to use a piece of opaque, elasticized cloth attached to both sides of the opaque block. This cloth forms both a finger support and a light shield. Figure 4 illustrates both types of finger transducers.

The photocell, lamp, and ground plate are wired to a short length (three feet) of two-conductor shielded cable. This cable is terminated in a polarized three-pin plug.

Building The Bridge. The author built his bridge circuit in a 5″ x 4″ x 2″ metal box, as shown in Fig. 5, although any other similar container would suffice. The bridge elements (*R1, R2,* and *R3*) are supported on a pair of three-terminal strip assemblies. The two batteries are mounted on the sides of the box, the on-off switch (*S1*) is on the upper surface of the box, and the three-pin polarized connector to accept the output from the transducer is mounted on one end of the box. All wiring is point to point. The bridge output is taken via a length of phono cable, with the center lead going to the bridge, and the braid connected to the ground. This cable is terminated in a two-pin polarized plug for connection either to an oscilloscope or to the FET amplifier.

If the output of the bridge is used to feed a d.c. scope, the d.c. component of the bridge output can be removed by replacing *R2* and *R3* with a 25,000-ohm potentiometer. The output is then taken from the arm of the potentiometer which is adjusted to produce a zero voltage output (to ground) with no signal to the photocell.

Preamplifier. The approximate bridge output amplitude of a PPG signal is 0.05-volt peak to peak. Your scope should have a vertical sensitivity of at least 10 mV per cm (25 mV per inch) at one to two Hz. However, if your scope does not have this sensitivity, the FET preamplifier (schematic in Fig. 2) should be built.

This amplifier has two characteristics that may cause you some trouble. The first is that the tantalum input capacitor (*C1*) acts somewhat like a diode—it has a high resistance in one direction and a low resistance in the other. The second is the very long time constant of *R1C1*. Although this is a nuisance, it is important in passing the very low frequencies required by the PPG.

When using the PPG the output is at a d.c. level, transducer modulated about 25 mV in both directions. It is important that *C1* present its high-resistance side to this d.c. voltage, otherwise *C1* will bias the gate of *Q1* enough to make the amplifier inoperative. If you get no output from the amplifier (with an input signal from the bridge), reverse the capacitor end-for-end or reverse the battery powering the bridge. *DO NOT* reverse the battery supplying power to the FET.

The aggravating long *R1C1* time constant means that it may take anywhere from ten to fifteen seconds to charge *C1*. During this interval, the charging current passing through *R1* can bias the FET to pinchoff—the equivalent of cutoff in a bipolar transistor or vacuum tube. Therefore, after placing your finger in the transducer, you might have to wait fifteen seconds before the amplifier commences functioning and the signal appears on the CRT. To partially eliminate this delay, a momentary-contact switch (*S2* in Fig. 2) is connected across *R1*. With this switch closed, *C1* will charge in a fraction of a second. When you release this switch, the amplifier should function immediately.

The amplifier is built in a 4″ x 2¼″ x 2¼″ metal box as shown in Fig. 6. Short leads should be used, as excessive capacitance between the output and input leads may lead to instability. Also, a good quality transistor socket is used to mount *Q1*. Since the signal of interest is in the millivolt range, the circuit should be shielded and good r.f. wiring techniques should be used to keep stray 60-Hz a.c. to a minimum. The input two-pin connector must match the plug coming from the bridge circuit, making sure that like leads are in contact—that is, hot lead to hot input, and ground braid to ground. The output of the preamplifier is a length of shielded microphone cable, with a termination plug suitable for attaching to your scope.

Using the PPG. Connect the transducer to the bridge, the bridge to the FET

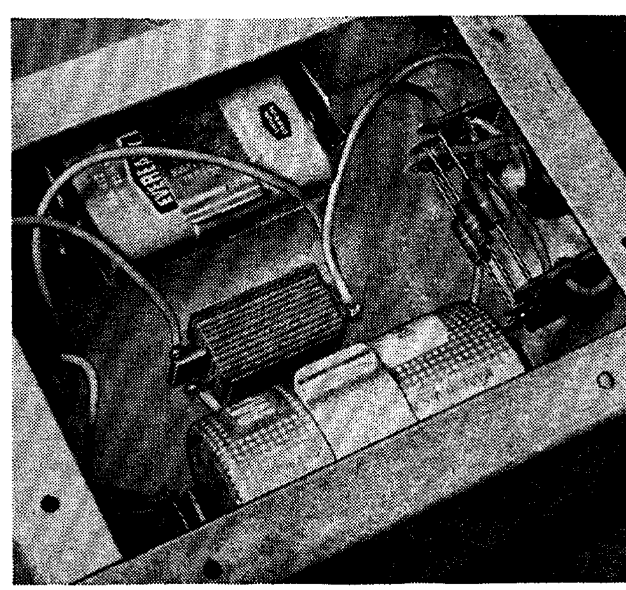


Fig. 5. The bridge circuit—excluding photocell and light source—is assembled with point-to-point wiring.

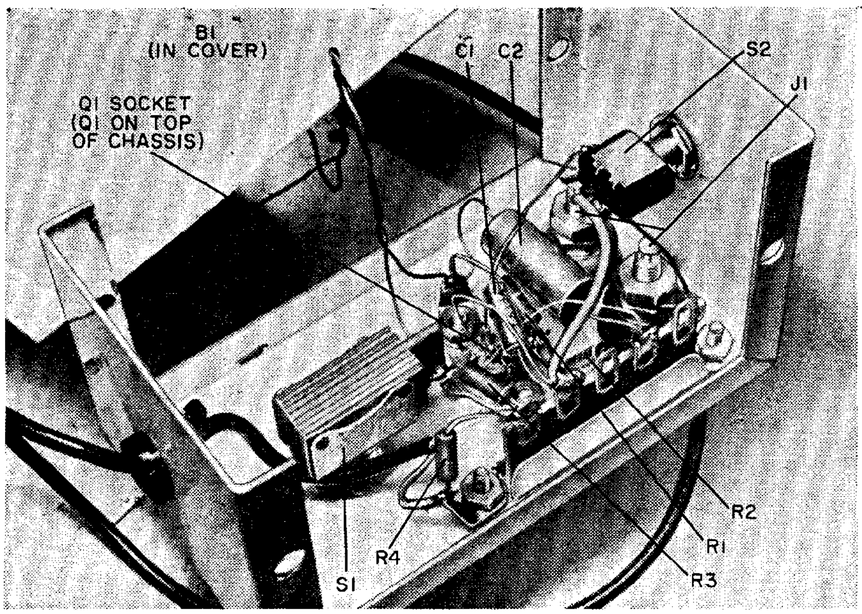


Fig. 6. Use point-to-point wiring when assembling the FET preamplifier. The circuit must be shielded to avoid electrical noise pick-up. Author mounted capacitor loading switch S2 on end plate of metal box and power switch S1 on top panel.

WHAT DOES THE PPG DISPLAY?

The photoplethysmograph (PPG) when connected to an appropriate oscilloscope displays pulsations of blood in the vascular system. These pulsations originate in the action of the heart and the PPG shows their amplitude, frequency and waveform.

Blood pressure (PPG amplitude) is displayed in three phases: "systolic," during contraction of the heart when arterial pressure is maximum; "diastolic," when the heart is expanding and pressure is low; and "mid-point," or mean, which occurs between the two extremes and is called the pulse pressure.

There is no normal PPG amplitude although there is a direct correlation between blood pressure and the peak response displayed by the PPG. Blood pressure of the subject varies according to age, physical condition, emotional state, etc. It also varies in different parts of the vascular system. The large arteries have higher pressure while the capillaries at the finger tips have a moderately low pressure.

The frequency rate of the pulse display is also variable—from an abnormal low of 50 pulses per minute to a high of 150, or more, pulses per minute. The velocity of the pulse wave through the vascular system is about 7 meters per second, although the actual blood flow is around 0.5 meters per second. If you attempt to correlate the actual heart beat and the PPG display, you will see a displacement due to the time lag in the flow of the blood through the arteries.

Because of the many variables, a strict interpretation of the PPG display is best left to the professional. However, as indicated in the article text, the PPG offers an opportunity to examine blood flow in the human body and the reaction of the heart to stress or emotional upset and physical exertion.

preamp (if used), and the preamp to the d.c. scope vertical input. If the preamp is not used, connect the bridge output directly to the oscilloscope. Make sure that the polarity of each signal lead is correct. Turn on the scope and adjust for a very slow horizontal sweep rate—one every two seconds is a good place to start—otherwise, set the sweep to as slow a rate as possible with your particular scope. If your scope has provisions for hooking an external capacitor to the horizontal sweep circuit, select a capacitor that produces a sweep time between one and 10 seconds. Capacitance values depend on the particular scope.

Set the scope vertical gain high, as the signal to be observed will be of low amplitude. Turn the bridge on-off switch *on* and check that the transducer light bulb goes on simultaneously. One interesting aspect of the transducer is that the brightest light source does not necessarily produce the strongest output signal. Some commercial PPG's use a rheostat in series with the light bulb so that light intensity can be controlled. Starting with maximum brightness, the lamp is gradually dimmed until a point is reached where the amplitude of the output signal peaks. The explanation for this behavior becomes clear when you recall that the PPG photocell is most sensitive in the *red* region of the visible light spectrum. A light bulb at full brilliance is putting too much of its energy in the blue spectrum, where the cadmium selenide photocell used in this project is "blind." This is why the *I1* is operated at approximately half voltage.

Insert a finger into the transducer light shield so that the ball of your fingertip rests comfortably across the two holes containing the light bulb and photocell. If you use either the spring clip or elastic band finger retainer, make sure that it does not push down too hard on your finger, as this will cut off the blood flow to the fingertip and reduce the output signal.

If you are using the FET preamplifier, close the capacitor switch for a couple of seconds, and adjust the scope vertical position until the trace is centered on the screen.

Do not wiggle your finger while making PPG measurements, as this will cause the trace to dart up and down the scope face.

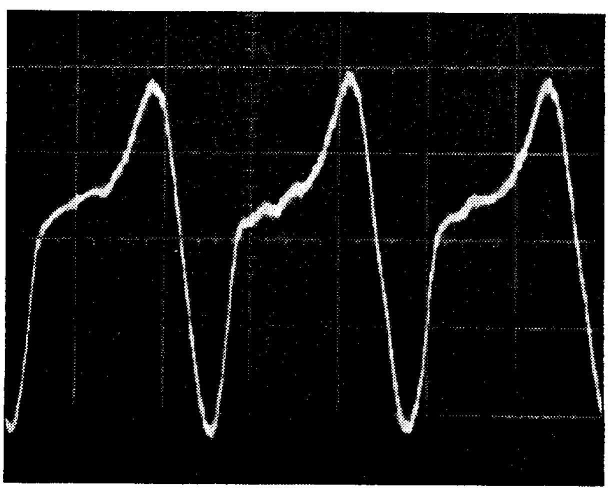


Fig. 7. Typical PPG displayed waveform. The trace shows fuzziness due to electrical noise pick-up.

After the trace settles down, you will see it assume a waveform similar to that shown in Fig. 7. (The waveform seen on the scope face on the cover is an approximate three-second time exposure.) The upward trace (downward if you have reversed the battery in the bridge circuit) is caused by an increase in blood volume due to a momentary dilation of the blood vessels. This in turn is caused by a pressure wave originating in the heart with each heart beat. This sharp contraction of the heart is called "systole" in medical terms. Naturally, the upward pulse trace will occur somewhere between 60 and 120 times each minute, corresponding to your heart rate. Variations in rate or amplitude, which represent an increase or decrease in blood volume, are easily seen.

To observe the action of the heart, stand up, hold your hand at heart level, and observe the trace. Then raise your hand as high as you can (wait for the trace to settle if it should flick off the scope face), and note the difference in the amplitude of the pressure wave. You can also lie down, with the transducer at heart level, note the waveform, then raise the hand as high as possible.

While observing the waveform, grasp the wrist of the hand attached to the transducer and start squeezing—gently at first, then more firmly. The amount of pressure required to flatten the scope trace will depend on your blood pressure. A pneumatic cuff and mercury manometer may be used with the PPG to determine your actual blood pressure.

You know that the tempo of your heartbeat will increase with exercise (such as a few quick, deep-knee bends), but what happens to the shape of the waveform? Try it and see. Also, try holding your breath after inhaling deeply—you might find that your pulse rate will accelerate at first, then decelerate, then speed back up again. There will be surprising changes in the amplitude of the pulse wave.

Emotions also have a powerful effect on blood circulation. If you experience stress, anger, or fear, your peripheral blood vessels will constrict and lessen the blood flow. It is difficult to duplicate these strong emotions under artificial conditions. However, be alert and you may note changes in the PPG waveforms that correspond to changes in the subject's emotional state.

Other, more practical uses, can also be demonstrated. The PPG can be used as an indicator of whether or not blood flow has been cut off in an arm while practicing with a tourniquet or using "pressure points" in practicing first-aid procedures. You can even apply the PPG transducer to a leg (connect the transducer to a toe) and check for the proper application of pressure points used to stop leg bleeding.

Cigarette smoking causes cutaneous vasoconstriction—reduction of blood flow in the skin. Smokers may observe this effect by taking a few deep "drags" on a cigarette while monitoring a PPG scope trace. —30—