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An Electrical Capacitance Diaphragm Manometer

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A new type of diaphragm manometer for direct pressure measurements in the arterial blood stream and in other fluid systems is described using a radiofrequency, crystal-controlled oscillator and a pressure-sensitive condenser in the pick-up unit. The potential drop due to the plate current of the oscillator tube flowing through a resistor is amplified, and is observed and photographed by means of a cathode-ray tube. Sensitivity control is obtained by the use of an inverse feed-back network in the amplifier. The range of sensitivity is from a maximum of one mm Hg per inch of cathode-ray tube spot deflection to any desired minimum. The approximate cut-off frequency of the manometer is 580 c.p.s. when used with a number 20 needle, 475 c.p.s. with a number 22 needle and 205 c.p.s. with a number 26 needle, each one inch long. These values are higher than those of previous diaphragm manometers with the same size liquid system and the same size needle. Sample records of the arterial pressure are presented.

IT has been shown that the metallic diaphragm (membrane) manometer has certain advantages over other types of manometers in the direct measurement of blood pressure[1] and other physiological pressures. These advantages are high frequency response, small volume change with pressure changes (high volume modulus of elasticity), and fair sensitivity. Optical recording was originally used;[1] the sensitivity was improved without resorting to inconveniently long optical paths.[2] However, optical methods not using a photo-cell are inherently inconvenient, necessitating fixation of the diaphragm with respect to the recording device. This disadvantage can be overcome by using electrical translation, as in the following methods: (1) keeping the mirror-diaphragm and adding a photo-cell; (2) reflecting light directly from the polished diaphragm surface into a photo-cell;[3] (3) measuring the change in resistance in a magnetic field of bismuth coils on the diaphragm;[4] (4) allowing the diaphragm to act as the movable plate of an electrical capacitance and measuring the variations in capacity by means of a radio-frequency circuit. This latter principle has been

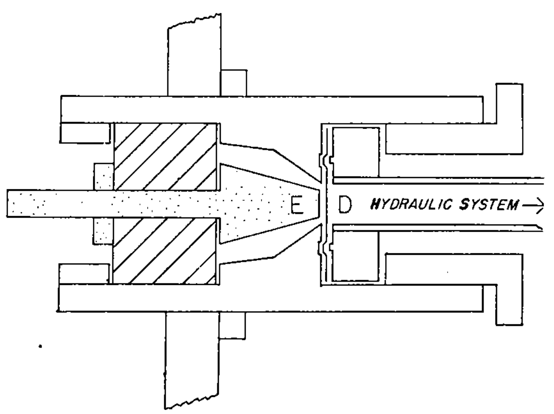

FIG. 1. Plan of the diaphragm and electrode holder. *E* is the electrode and *D* is the diaphragm. The diagonally lined area is the glass tubing dielectric used to support the electrode. The holder is shown fastened into the wall of the oscillator housing. This drawing is to scale. The active portion of the diaphragm exposed to the liquid is one-fourth of an inch in diameter.

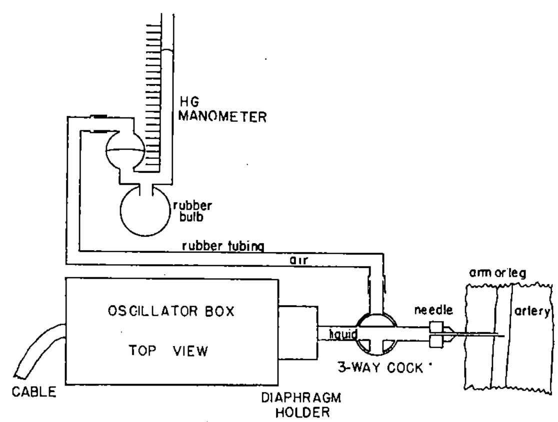

FIG. 2. Schema of the operation and calibration of the e.c.d. manometer. The clamp used in adjusting the height of the mercury column in the Hg manometer is not shown; this clamp is placed so as to compress the rubber bulb on the Hg manometer. The stopcock is shown in the operating position; this cock is turned ninety degrees clockwise for calibrating purposes.

[1] W. F. Hamilton *et al.*, Am. J. Physiol. **107**, 427 (1934).
[2] D. E. Gregg, Am. J. Physiol. **119**, 321 (1937).
[3] A. F. Robertson, Rev. Sci. Inst. **12**, 142 (1941).
[4] Albert Hampel, Pflugers Arch. Ges. Physiol. **244**(2), 171–175 (1940).

used in measuring pressure in engine cylinders,[5,7] and also in measuring extremely small displacements (10^{-6} mm).[6] The apparatus herein described uses the radiofrequency-capacitance principle, and hence is called the electrical capacitance diaphragm manometer (e.c.d. manometer).

DESCRIPTION OF THE INSTRUMENT

The manometer consists of a hydraulic system with the needle for arterial puncture at one end and the metal diaphragm at the other, a radiofrequency oscillator, a direct-coupled differential voltage amplifier and a cathode-ray oscillograph. The stainless steel needle (gauge No. 23, length 1.0 inch) is fastened by means of a Luer-lok to a short length of stainless steel tubing. The tubing is connected to the diaphragm holder (Fig. 1) through a stainless steel 3-way stopcock. The diaphragm (nickel, 0.005 inch thick, $\frac{1}{4}$ inch in diameter) is clamped tightly over the end of the stainless steel tube by means of a threaded cover, and is held 0.0005 of an inch from the electrode ($\frac{3}{16}$ inches in diameter). Unless the electrode surface is parallel to the diaphragm at this spacing with the small electrode diameter used, the sensitivity will be too small to be useful. A small rigid metal box ($4\times3\frac{1}{2}\times2$ inches with a wall $\frac{3}{16}$ inch thick) houses the diaphragm, the oscillator tube and the radiofrequency circuit (Fig. 2 and Fig. 3).* A flexible cable to the amplifier carries the heater and direct-current conductors for the oscillator.

FIG. 4. Calibration record using modified hydraulic system without the stopcock, and applying the calibration pressure to the air space around the electrode. All records are from a dog's femoral artery. Blood pressure equals 120/80 mm Hg. Calibrating pressure was 80 mm Hg, thus bringing the apparent diastolic pressure during the calibration period to the atmospheric level on the cathode-ray tube screen. The sensitivity is approximately 100 mm Hg per inch of cathode-ray tube deflection.

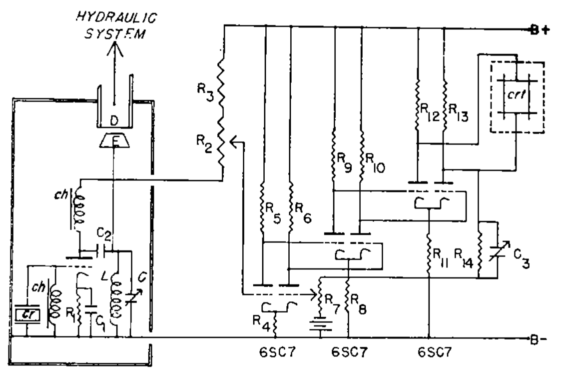

FIG. 3. Circuit of the e.c.d. manometer. The oscillator tube is Type 1620 connected as a triode. The amplifier tubes are all Type 6SC7.

cr	quartz crystal, 14 megacycles
crt	cathode-ray tube
ch	radiofrequency choke
L	tank coil (30 turns No. 22 wire on $\frac{3}{4}''$ ceramic form)
C	vibration-proof trimmer condenser 6–30 $\mu\mu$f (Centralab)
D	diaphragm
E	electrode
C_1	0.006 μf (bypass) condenser
C_2	0.006 μf (plate blocking) condenser
C_3	5–35 $\mu\mu$f (feedback) trimmer condenser
R_1	400-ohm 10-watt wire wound (cathode) resistor
R_2	20,000-ohm wire-wound (position setting) 3-decade resistor
R_3	100,000-ohms wire-wound resistor
R_4	73,000 ohms 1-watt wire-wound
R_5R_6	500,000 ohms 1-watt wire-wound
R_7	500, 250, 100, 50, 25, 10 kilo-ohms, wire wound in series
R_8	350,000-ohms 1-watt
R_9R_{10}	1-megohm 1-watt
R_{11}	750,000-ohms 1-watt
$R_{12}R_{13}$	1-megohm 1-watt
R_{14}	20-megohms, $\frac{1}{2}$-watt
$B+$	410 volts

The electrical system consists of an oscillator, amplifier, and a cathode-ray oscillograph as an indicator (Fig. 3). The oscillator circuit is a conventional one with a high frequency crystal. The resonant tank circuit consists of a coil and two condensers, one of which comprises the diaphragm and the electrode; the other is a vibration-proof ceramic trimmer covering the range from 6 $\mu\mu$f to 30 $\mu\mu$f. As can be seen from the wiring diagram, the amplifier actually measures the voltage drop through the oscillator plate load resistor (10^5 ohms). The plate current and hence the voltage drop varies with the capacitance in the tank circuit when the capacitance is adjusted to one side or the other of the crystal resonant point. The steep side of the

[5] L. C. Roess, Rev. Sci. Inst. **11**, 183 (1940).
[6] D. W. Dana, Rev. Sci. Inst. **5**, 38 (1934).
[7] C. H. Brookes-Smith *et al*, J. Sci. Inst. **16**, 361 (1939).

* A subsequent model has a housing only $1\times1\times6$ inches, achieved by using smaller, more closely spaced oscillator components.

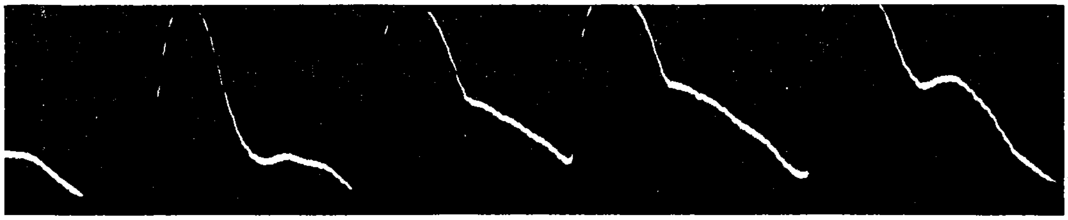

FIG. 5. Femoral pressure wave form. The sensitivity was raised to 8-mm Hg pressure per deflection inch.

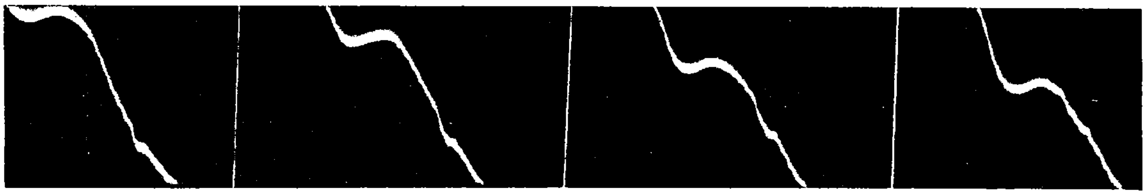

FIG. 6. Femoral pressure wave form. Detail in the falling portion of the pressure cycle. The sensitivity is 4 mm Hg per deflection inch. The vertical white line was drawn in to correspond to the rising pressure portion of the cycle which photographed but dimly at this high sensitivity.

resonance curve is chosen for operation of the oscillator. On this side of the curve the d.c. plate voltage increases as the capacitance in the tank circuit increases. With a 410-volt d.c. plate supply and a 1620 tube operating as a triode at a frequency of 14 megacycles, the plate voltage should be adjusted to about 45 to 50 volts. This adjustment should be made whenever the diaphragm is replaced. The radiofrequency circuit was chosen to give a minimum number of components in order to minimize vibration instabilities and to make the pick-up unit small. Ultimately a circuit employing a radiofrequency, flexible, concentric line to the signal capacitance may prove more practical.[5,7] The amplifier is a conventional, direct-coupled, differential voltage amplifier. The tubes (6SC7) are selected for close match of the two triode sections. Sensitivity and band pass control are regulated by a negative or inverse feed-back net. A small variable (trimmer) condenser is placed across this feed-back network to cut off the higher, unused portion of the amplifier's pass band. The power for the oscillator and amplifier may be derived from batteries or from a regulated power supply.

In filling the hydraulic system a solution of sodium citrate (5 percent) can be used to prevent blood coagulation. This should be sterile, and also should have been recently boiled to remove dissolved gases. It can be introduced into the system by the use of a syringe and a long (6-inch) needle of 22 gauge. The slightest leak (even a small fraction of a cubic millimeter) will allow blood to enter the small needles employed, and clotting will develop. Similarly the lowering of the volume modulus of elasticity that results from the presence of bubbles not only lowers the natural frequency of the system, but also allows the blood to enter the needle. Bubbles and leaks can be detected by pushing the needle into a rubber stopper to plug its open end, applying about 200-mm Hg pressure to the liquid system, and then turning the stopcock so as to close off the side arm and open the diaphragm and needle tubes to one another. If the pressure level then remains high, there is probably no leak or bubble. If the pressure falls to atmospheric level, there is probably a leak in the system. If the pressure falls and then levels off at some value greater than atmospheric, there is probably a bubble present. Preferably bubbles should be detected by Hamilton's method.[1] Their occurrence may be lessened by use of Zephiran (Alba Pharmaceutical Company, New York City) (courtesy of Dr. Rudolph Hoeber) added to the citrate after boiling to give a concentration of 1 to 2500. This substance acts as a wetting agent and also as a powerful antiseptic. In later models the stopcock has been eliminated with the result that leaks no longer occur (Fig. 4). Bubble formation also has been greatly reduced. Because of the small volume change of the liquid system with a given pressure change (using the above diaphragm), little, if any, blood enters even the small needles used. A number 20 gauge needle in a dog's femoral artery has been used for two hours and a quarter without being plugged by a clot (Figs. 4, 5, 6). The manometer may be standardized before, during, and after a blood pressure determination by adjusting the pressure in the air system (Fig. 2) by means of the mercury manometer and applying this known pressure to the diaphragm by turning the stopcock.

The introduction of the needle into the artery is best attained by the use of an inclined-plane support to carry the weight of the pick-up unit. For the human brachial artery the elbow is extended, and the inclined plane is adjusted so that the needle on introduction through the skin will enter the artery. Maintenance of the system involves mainly an avoidance of infections. Immediately after use, the system is washed out with water, and filled with alcohol. If a series of observations is to be made on different subjects, it is only necessary to replace the used needle with another clean, filled one.

CHARACTERISTICS OF THE MANOMETER

A pure nickel diaphragm 0.005 inch thick and 0.25 inch in diameter gives a maximum over-all sensitivity, with the present amplifier, of one mm Hg per inch of cathode-ray tube spot deflection. Any desired minimum over-all sensitivity, such as 200 mm Hg per deflection inch can be used by suitable values in the feed-back circuit in the amplifier. The cut-off frequency of the manometer with the above diaphragm is approximately 580 c.p.s. with a number 20 needle, 475 c.p.s. with a number 22 needle, 205 c.p.s. with a number 26 needle, each one inch long. These values are higher than those of previous diaphragm manometers with the same size liquid system and the same size needle. When tested by Hamilton's method the overshoot was less than one percent. The calculated volume displacement is less than 10^{-6} cc/100 mm Hg. The stability of calibration is adequate for most physiological work, provided that the apparatus be turned on and allowed to warm up for about one hour. The absolute and relative calibrations then remain constant for several hours. The stability over longer periods has not yet been investigated.

The pick-up unit is independent of motion or position changes, can be placed up to twenty feet from the recorder without introducing distortion into the recording, and can be used with two cathode-ray tubes for observation and photographic records. For transmission of the signal distances greater than twenty feet and for use with more than two cathode-ray tubes, cathode-coupled impedance changing tubes in the amplifier input and output can be used to avoid distortion of the higher signal frequencies. The electrical conductor from the pick-up unit to the amplifier can be treated as any other shielded electrical cable: run through walls or conduits, sealed into air or liquid proof joints, etc. The small needles (No. 23 through No. 26) used in this manometer allow arterial puncture in the conscious human subject to be relatively painless, reduce the probability of infection, make possible long continuous observation periods without withdrawal and re-insertion, and cause little trauma after multiple insertions into the same artery.

Subsequent models of the instrument point to some interesting developments. The stopcock has been eliminated by applying the calibration pressure to the air space around the electrode (Fig. 1), instead of to the liquid side of the diaphragm. With a suitable amplifier the electrical sensitivity can be increased greatly before reaching the inherent noise level. The displacement sensitivity can be raised (keeping the diaphragm constant) by using a high dielectric-constant fluid (such as pure glycerin) in the space between the electrode and the diaphragm. The use of a dielectric liquid instead of air in the inclosed space about the electrode allows the apparatus to be used as a sensitive differential manometer conceivably useful in liquid flow and similar measurements. For special purposes involving small pressure changes, small silvered, blown glass diaphragms and a special electrode holder were constructed, tried, and found to be extremely sensitive.

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