Chapter 15-Pressure Measurement

6.2.3. Direct Measurements

In 1728, Hales inserted a glass tube into the artery of a horse and crudely measured arterial pressure. Poiseuille substituted a mercury manometer for the piezometer tube of Hales, and Ludwig added a float and devised the *kymograph,* which allowed continuous, permanent recording of the blood pressure. It is only quite recently that electronic systems using strain gages as transducers have replaced the kymograph.

Regardless of the electrical or physical principles involved, direct measurement of blood pressure is usually obtained by one of three methods:

1. Percutaneous insertion.
2. Catheterization (vessel cutdown).
3. Implantation of a transducer in a vessel or in the heart.

Other methods, such as clamping a transducer on the intact artery, have also been used, but they are not common.

Figure 6.18 should give a general idea of both methods. Typically, for percutaneous insertion, a local anesthetic is injected near the site of invasion. The vessel is occluded and a hollow needle is inserted at a slight angle toward the vessel. When the needle is in place, a catheter is fed through the hollow needle, usually with some sort of a guide. When the catheter is securely in place in the vessel, the needle and guide are withdrawn. For some measurements, a type of needle attached to an airtight tube is used, so that the needle can be left in the vessel and the blood pressure sensed directly by attaching a transducer to the tube. Other types have the transducer built into the tip of the catheter. This latter type is used in both percutaneous and full catheterization models.

Catheterization was first developed in the late 1940s and has become a major diagnostic technique for analyzing the heart and other components of the cardiovascular system. Apart from obtaining blood pressures in the heart chambers and great vessels, this technique is also used to obtain blood samples from the heart for oxygen-content analysis and to detect the location of abnormal blood flow pathways. Also, catheters are used for investigations with injection of radiopaque dyes for X-ray studies, colored dyes for indicator dilution studies, and of vasoactive drugs directly into the heart and certain vessels. Essentially, a *catheter* is a long tube that is introduced into the heart or a major vessel by way of a superficial vein or artery. The sterile catheter is designed for easy travel through the vessels.

Measurement of blood pressure with a catheter can be achieved in two ways. The first is to introduce a sterile saline solution into the catheter so that the fluid pressure is transmitted to a transducer outside the body (extracorporeal). A complete fluid pressure system is set up with provisions for checking against atmospheric pressure and for establishing a reference point. The frequency response of this system is a combination of the frequency response of the transducer and the fluid column in the catheter. In the second method, pressure measurements are obtained at the source. Here, the transducer is introduced into the catheter and pushed to the point at which the pressure is to be measured, or the transducer is mounted at the tip of the catheter. This device is called a *catheter-tip blood pressure transducer.* For mounting at the end of a catheter, one manufacturer uses an unbonded resistance strain gage in the transducer, whereas another uses a variable inductance transducer (see Chapter 2). Each will be discussed later.

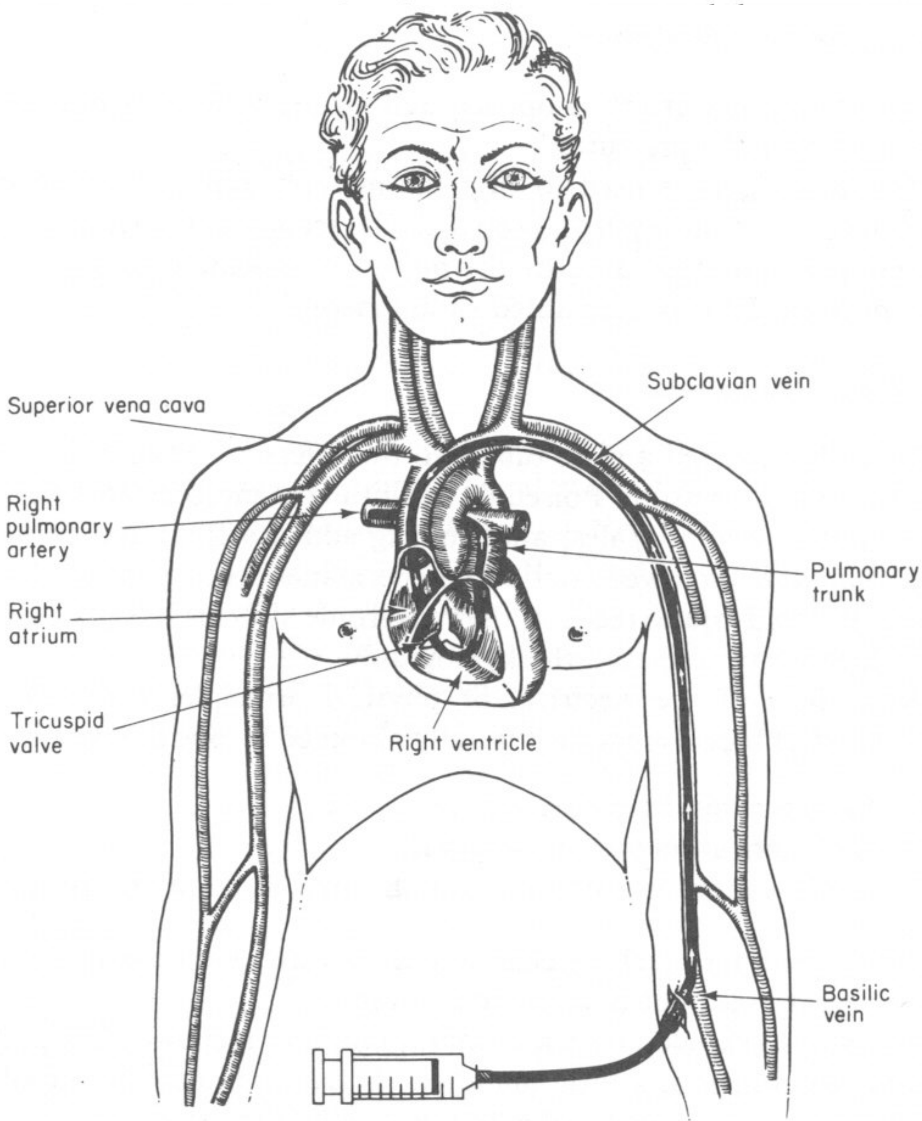

Figure 6.18. Cardiac catheterization. The tube is shown entering the basilic vein in this case. (From W.F. Evans, *Anatomy and Physiology, The Basic Principles,* Englewood Cliffs, NJ., Prentice-Hall, Inc., 1971, by permission.)

Implantation techniques involve major surgery and thus are normally employed only in research experiments. They have the advantage of keeping the transducer fixed in place in the appropriate vessel for long periods of time. The type of transducer employed in that procedure is also described later in this section.

Transducers can be categorized by the type of circuit element used to sense the pressure variations, such as capacitive, inductive, and resistive. Since the resistive types are most frequently used, the other two types are discussed only briefly.

In the *capacitance manometer,* a change in the distance between the plates of a capacitor changes its capacitance. In a typical application, one of the plates is a metal membrane separated from a fixed plate by some one-thousandth of an inch of air. Changes in pressure that change the distance between the plates thereby change the capacitance. If this element is contained in a high-frequency resonant circuit, the changes in capacitance vary the frequency of the resonant circuit to produce a form of frequency modulation. With suitable circuitry, blood pressure information can be obtained and recorded as a function of time.

An advantage of this type of transducer is that its total contour can be long and thin so that it can be easily introduced into the bloodstream without deforming the contour of the recorded pressure waveform. Because of the stiff structure and the small movement of the membrane when pressure is applied, the volume displacement is extremely small (in the region of 10^{-6} cm^3/100 mm Hg of applied pressure).

Disadvantages of this type of transducer are instability and a proneness to variations with small changes in temperature. Also, lead wires introduce errors in the capacitance, and this type of transducer is more difficult to use than resistance types.

A number of different devices use inductance effects. They measure the distortion of a membrane exposed to the blood pressure. In some of these types, two coils are used—a primary and secondary. When a spring-loaded core that couples the coils together magnetically is moved back and forth, the voltage induced into the secondary changes in proportion to the pressure applied.

A better-known method employs a *differential transformer,* described in detail in Chapter 2. In this device two secondary coils are wound oppositely and connected in series. If the spring-loaded core is symmetrically positioned, the induced voltage across one secondary coil opposes the voltage of the other. Movement of the core changes this symmetry, and the result is a signal developed across the combined secondary coils. The core can be spring-loaded to accept pressure from one side, or it can accept pressure from both sides simultaneously, thus measuring the difference of pressure between two different points.

The *physiological resistance transducer* is a direct adaptation of the strain gages used in industry for many years. The principle of a strain gage is that if a very fine wire is stretched, its resistance increases. (A detailed discussion of strain gages is given in Chapter 2.) If voltage is applied to the resistance, the resulting current changes with the resistance variations according to Ohm's law. Thus, the forces responsible for the strain can be recorded as a function of current. The method by which the blood pressure produces the strain is discussed in Section 6.2.4.

To obtain the degree of sensitivity required for blood pressure transducers, two or four strain gages are mounted on a diaphragm or membrane, and these resistances are connected to form a bridge circuit. Figure 6.19 shows such a circuit configuration.

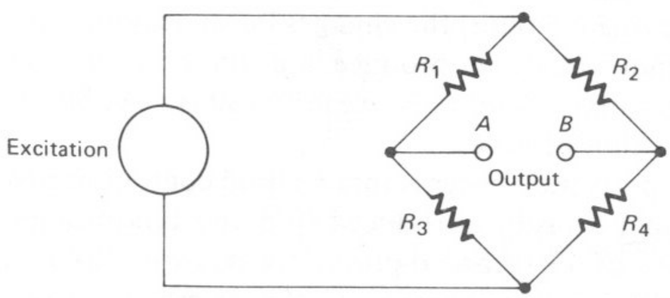

Figure 6.19. Resistance strain-gage bridge.

In general, the four resistances are initially about equal when no pressure or strain is applied. The gages are attached to the pressure diaphragm in such a way that as the pressure increases, two of them stretch while the other two contract. An excitation voltage is applied as shown. When pressure changes unbalance the bridge a voltage appears between terminals *A* and *B* proportional to the pressure. Excitation can be either direct current or alternating current, depending on the application.

Resistance-wire strain gages can be *bonded* or *unbonded* (see Chapter 2). In the bonded type, the gage is "bonded" to the diaphragm and stretches or contracts with bending. The unbonded type consists of two pairs of wires, coiled and assembled in such a way that displacement of a membrane connected to them causes one pair to stretch and the other to relax. The two pairs of wires are not bonded to the diaphragm material but are attached only by retaining lugs. Because the wires are very thin, it is possible to obtain relatively large signals from the bridge with small movement of the diaphragm.

Development of semiconductors that change their resistance in much the same manner as wire gages has led to the *bonded silicon element* bridge. Only small displacements (on the order of a few micro meters) of the pressure-sensing diaphragm, are needed for sizable changes of output voltage with low-voltage excitation. For example, with 10 V excitation, a range of 300 mm Hg is obtained with a 3-μm deflection, producing a 30-mV signal.

Semiconductor strain-gage bridges are often temperature-sensitive, however, and have to be calibrated for baseline and true zero. Therefore, it is usually necessary to incorporate external resistors and potentiometers to balance the bridge initially, as well as for periodic correction.

In Chapter 2 the gage factor for a strain gage is defined as the amount of resistance change produced by a given change in length. Wire strain gages have gage factors on the order of 2 to 4, whereas semiconductor strain gages have gage factors ranging from 50 to 200. For silicon, the gage factor is typically 120. The use of semiconductors is restricted to those configurations that lend themselves to this technique.

When strain gages are incorporated in pressure transducers, the sensitivity of the transducer is expressed, not as a gage factor, but as a voltage change that results from a given pressure change. For example, the sensitivity of a pressure transducer can be given in microvolts per (applied) volt per millimeter of mercury.

6.2.4. Specific Direct Measurement Techniques

In Section 6.2.3 methods of direct blood pressure were classified in two ways, first by the clinical method by which the measuring device was coupled to the patient and, second, by the electrical principle involved. In the following discussion, the first category is expanded, with the electrical principles involved being used as subcategories where necessary. The four categories are as follows:

1. A catheterization method involving the sensing of blood pressure through a liquid column. In this method the transducer is external to the body, and the blood pressure is transmitted through a saline solution column in a catheter to this transducer. This method can use either an unbonded resistance strain gage to sense the pressure or a linear variable differential transformer. Externally, these two devices are quite similar in appearance.
2. A catheterization method involving the placement of the transducer through a catheter at the actual site of measurement in the bloodstream (e.g., to the aorta), or by mounting the transducer on the tip of the catheter.

3. Percutaneous methods in which the blood pressure is sensed in the vessel just under the skin by the use of a needle or catheter.
4. Implantation techniques in which the transducer is more permanently placed in the blood vessel or the heart by surgical methods.

The most important aspects of these methods are discussed separately.

6.2.4.1. Liquid-column methods. A typical liquid-column blood pressure transducer, the Gould Statham P 23 ID, is illustrated in Figure 6.20. Figure 6.21 is a cutaway drawing to show the interior construction and the isolation features of the same transducer, which is considered a standard size in hospital practice. The heart of the P 23 transducer is the unbonded strain gage, which is connected in a standard Wheatstone bridge configuration. The metal sensing diaphragm can be seen on the left side. It is a precision-made part that must deflect predictably with a given fluid pressure. When the diaphragm is deflected downward by the pressure of the liquid being measured, the tension on two of the bridge wires is relaxed and the tension on the other two wires is tightened, changing the resistance of the gage. For negative pressures, the opposite wires are stretched and relaxed.

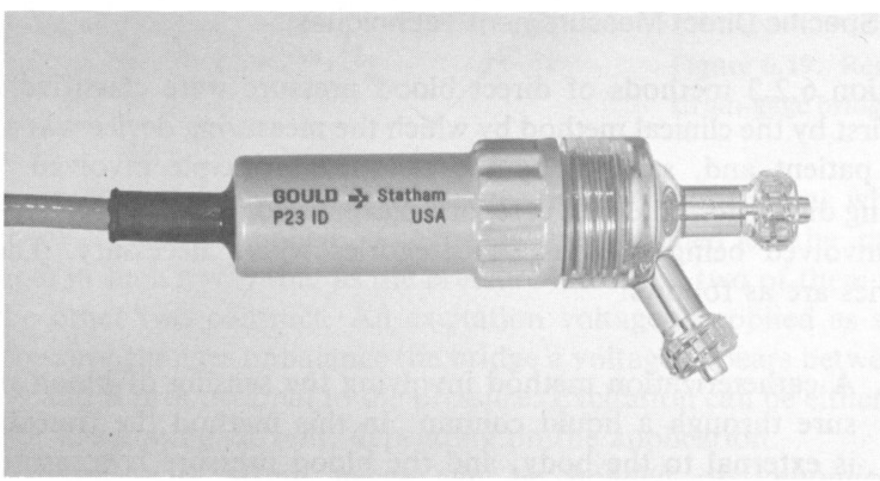

Figure 6.20. Fluid-column blood pressure transducer. (Courtesy of Gould, Inc., Measurement Systems Division, Oxnard, CA.)

The transducer is connected through the cable to an instrument which contains zero-balance and range controls, amplifier circuits, and a readout. The shielded cable is attached to the case through a liquid-tight seal that permits immersion of the transducer for cleaning. The transducer case is vented through the cable so that measurements are always referenced to atmospheric pressure.

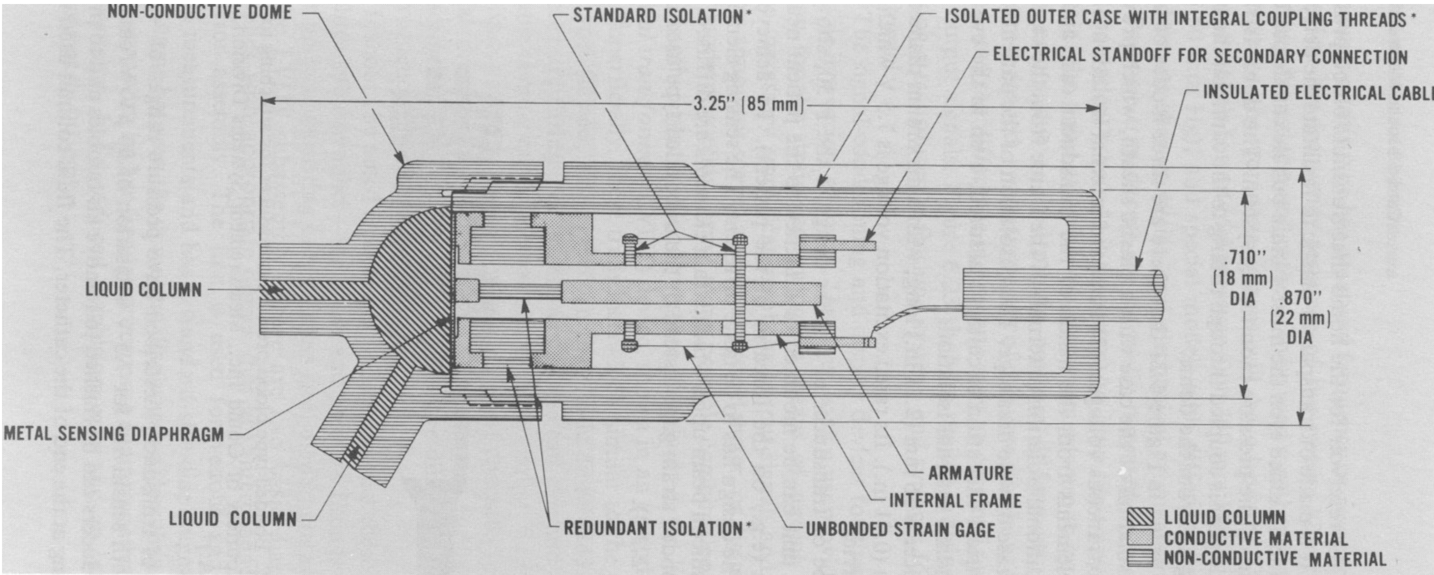

Figure 6.21. Interior construction of P23ID Blood Pressure Transducer. (Courtesy of Gould Inc., Measurement Systems Division, Oxnard, CA.)

The dome is the reservoir for the liquid that transmits blood pressure to the diaphragm. It is made of transparent plastic to facilitate the detection and removal of bubbles, since even the most minute bubble can degrade the frequency response of the pressure-monitoring system. The dome is fitted with two ports. One port is coupled through tubing to the cannula; the other is used for venting air from the dome.

It should be noted in Figure 6.21 that there are three modes of isolation: (1) external isolation of the case with a plastic sheath, which provides protection from extraneous voltages; (2) standard internal isolation of the sensing (bridge) elements from the inside of the transducer case and the frame; and (3) additional isolation (internal) of the frame from the case and the diaphragm in case of wire breakage. Thus, isolation of the patient/fluid column from electrical excitation circuitry is assured, even in the event of failure of the standard internal isolation.

This transducer is 56 mm (2.21 in.) long, with a maximum diameter at the base of 18 mm (0.71 in.). Its rated excitation voltage is 7.5 V which may be dc or an ac carrier.

Another type of transducer of smaller design is the P 50, shown in Figure 6.22. This unit can be mounted or attached to the patient near the measurement site (e.g., on the forearm of the patient). To achieve this miniaturization, the design has to be quite different. The sensing element of the P 50 is a tiny silicon beam upon which strain elements are diffused. This is, therefore, a bonded strain gage instead of the unbonded type used in the P 23 (see Section 2.3.1).

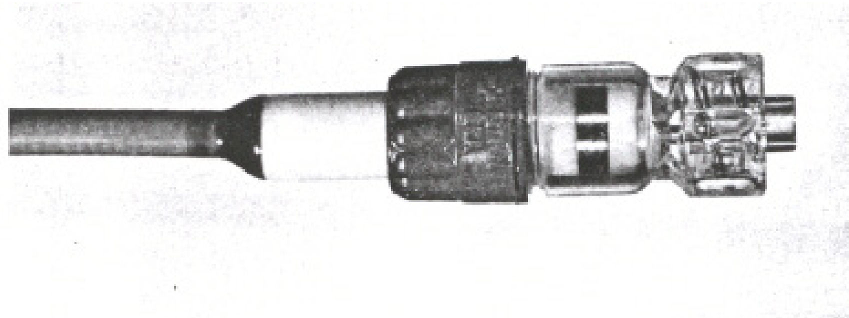

Figure 6.22. Bonded type blood pressure transducer for attaching to patient. (Courtesy of Gould Inc., Measurement Systems Division, Oxnard, CA.)

Both types of transducer described have pressure ranges of −50 to +300 mm Hg, with sensitivity for 7.5-V excitation of 50 μV/V/cm Hg.

These transducers can be flushed to remove air bubbles and to prevent blood from clotting at the end of the catheter. The fluid column used with a transducer of this type has a natural frequency or resonance of its own that can affect the frequency response of the system. Care must be taken in selecting a transducer and catheter to be used together so that the frequency response of the complete system will be adequate. There are general-purpose models for arterial pressure (0 to 330 mm Hg) and venous pressure (0 to 50 mm Hg), and special models with differing sensitivities, volume displacement characteristics, and mechanical arrangements.

Pressure transducers are normally mounted on a suitable manifold near the patient's bed. It is important to keep the transducer at the same height as the point at which the measurements are to be made in order to avoid errors due to hydrostatic pressure differences. If a *differential pressure* is desired, two transducers of this type may be used at two different points, and the difference in pressure may be obtained as the difference of their output signals. Figure 6.23 shows a typical infusion manifold incorporating a transducer, a flushing system, and syringes for blood specimen withdrawal.

The signal-conditioning and display devices for these transducers are available in a variety of forms. However, each must provide a method of excitation for the strain-gage bridge, a means of zeroing or balancing the bridge, necessary amplification of the output signal, and a display device, such as a monitor scope, a recorder, panel meter, or digital readout device. Most modern systems permit many possible combinations.

Another type of blood pressure transducer is the *linear variable differential transformer* (LVDT) device, shown in an exploded view in Figure 6.24. Superficially, these transducers look similar to the unbonded strain-gage type. Indeed, with respect to the plastic dome used for visibility, the two pressure fittings for attachment to the catheter and for flushing, and the cable coming out of the bottom, they are similar. Such transducers also come in a variety of models with a range of characteristics for venous or arterial pressure, for different sensitivities, and for alternative volume displacements. The various models also have different natural frequencies and frequency responses.

It should be noted from the exploded view that these units disassemble into three subassemblies—the dome and pressure fittings subassembly, the center portion consisting of a stainless-steel diaphragm and core assembly, and the LVDT subassembly. There are two basic diaphragm and core assemblies with appropriate domes that are interchangeable in the coil-connector assembly. The first is used for venous and general-purpose clinical measurements and has a standard-size diaphragm with an internal fluid volume between the dome and diaphragm of less than 0.5 cm^3. The second design, with higher frequency response characteristics for arterial pressure contours, has a reduced diaphragm area and an internal volume of approximately 0.1 cm^3.

The Biotronex BL-9630 transducer is a linear variable differential transformer in which the primary coil is excited by an ac carrier (5 to 20 V peak to peak) in the range of 1500 to 15,000 Hz. Axial displacement of a movable iron core, attached to the diaphragm, cuts the magnetic lines of flux generated by the primary coil. Voltages induced in the secondary sensing coils are returned to the carrier amplifier, where they are differentially amplified and demodulated to remove the carrier frequency. The output of the carrier amplifier is a dc voltage proportional to diaphragm displacement. Linearity of the gage is better than ± 1 percent of full range. Ordinary jarring and handling will not harm the gage. A positive mechanical stop is provided to prevent damage by as much as a 100 per-cent overpressure. The LVDT offers much higher signal levels than do conventional strain-gage transducers for a given excitation voltage.

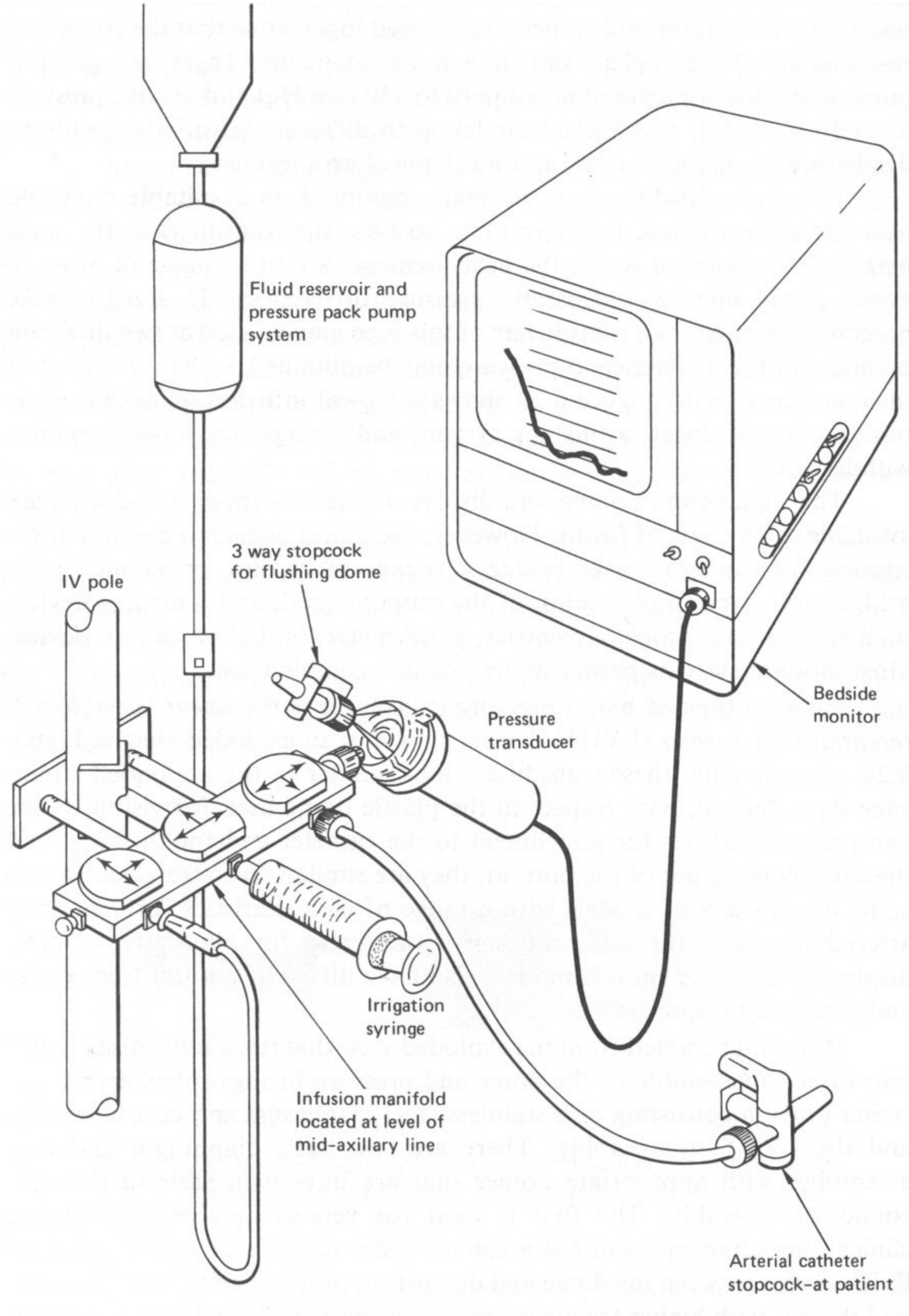

Figure 6.23. Infusion manifold with transducer, flushing system and syringe. (Courtesy of Michael Tomeo, UCLA Medical Center.)

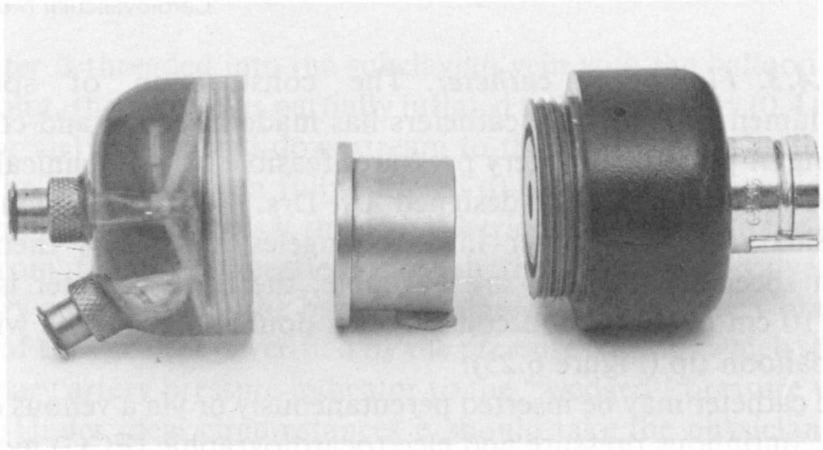

Figure 6.24. LVDT blood pressure transducer—exploded view. (Courtesy of Biotronex Laboratory, Inc., Silver Springs, MD.)

6.2.4.2. Measurement at the site. To avoid the problems inherent in measuring blood pressure through a liquid column, a "catheter-tip" manometer can be fed through the catheter to the site at which the blood pressure is to be measured. This process requires a small-diameter transducer that is fairly rigid but flexible.

One such transducer makes use of the variable-inductance effect mentioned earlier. The tip is placed directly in the bloodstream so that the blood presses on a membrane surrounded by a protective cap. The membrane is connected to a magnetic slug that is free to move within a coil assembly and thus changes the inductance of the coil as a function of the pressure on the membrane.

Another type has a bonded strain-gage sensor built into the tip of a cardiac catheter. The resistance changes in the strain gage are a result of pressure variations at the site itself rather than through a fluid column. This gage can also be calibrated with a liquid-system catheter at the same location.

6.2.4.3. Floatation catheter. The construction of specialized, multiple-lumen "floatation" catheters has made insertion and continuous monitoring of pulmonary artery pressures feasible in most clinical settings. This type of catheter was designed by Drs. Swan and Ganz of the Cedars–Sinai Medical Center in Los Angeles and bears their names. Although specialized models are available, the basic catheter is approximately 110 cm in length and consists of a double-lumen tube with an inflatable balloon tip (Figure 6.25).

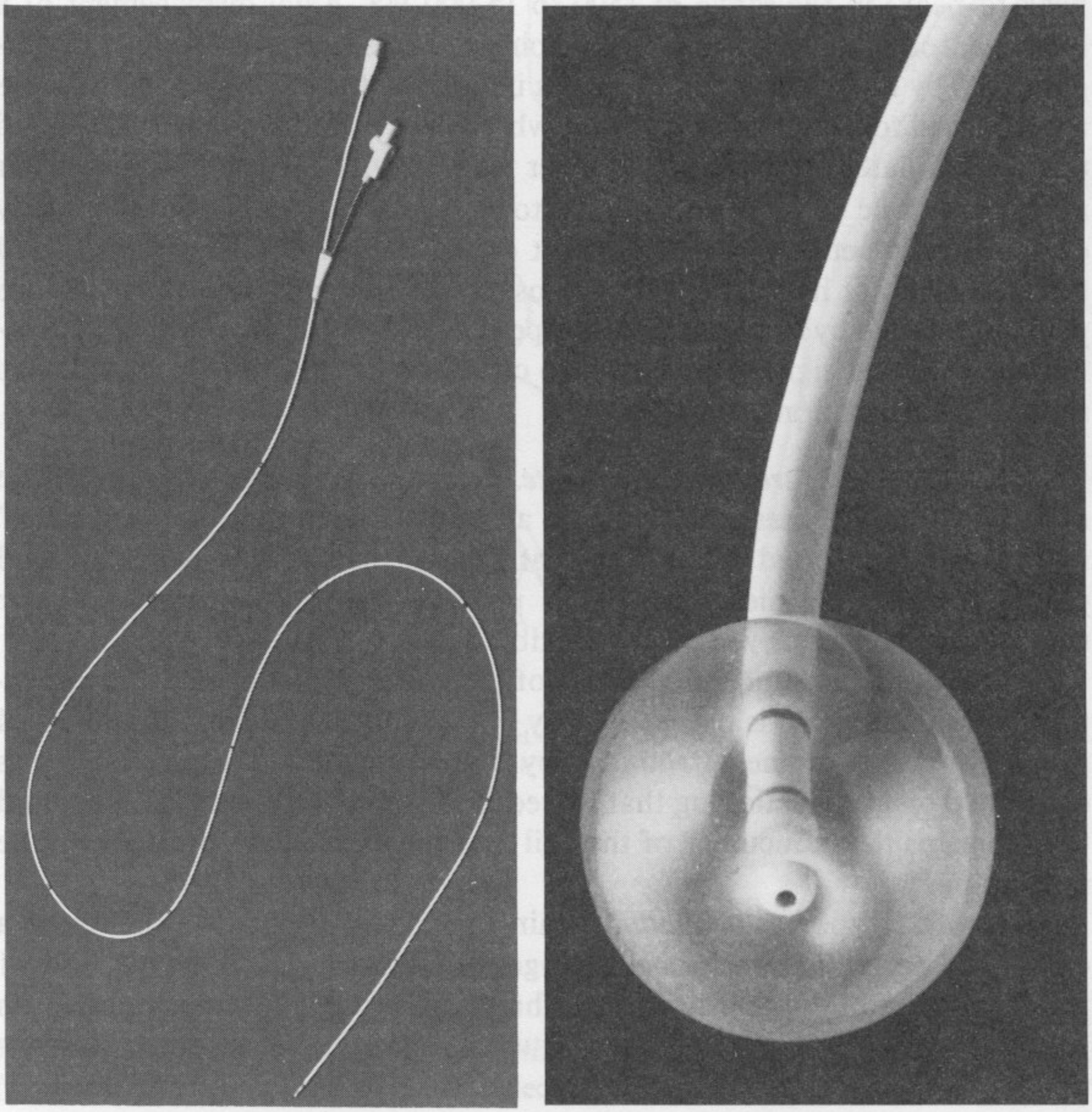

Figure 6.25. (a) Swan-Ganz monitoring catheter for measurement of pulmonary artery and pulmonary capillary wedge pressures, full view; (b) balloon. (Courtesy of Edwards Laboratories, Division of American Hospital Supply Corporation, Santa Ana, CA.)

The catheter may be inserted percutaneously or via a venous cutdown. By using continuous pressure and electrocardiographic (ECG) monitoring, the catheter is threaded into the subclavian vein with the balloon deflated. At this point, the balloon is partially inflated to half capacity (0.4 to 0.6 cm^3 of CO_2 or air) and carried downstream to the right atrium by the flow of blood. The balloon is then fully inflated (0.8 cm^3) and advanced again so that the blood flow propels it through the tricuspid valve into the right ventricle. From there it is carried through the pulmonary valve into the pulmonary artery, where the balloon wedges in a distal artery branch. The position of the catheter is verified by the pressure tracing, which shifts from a pulmonary artery pressure indicator to the "wedged" pressure waveform position. Under ideal circumstances it should take the physician no more than 1 minute to float the catheter from full balloon inflation in the right atrium to the wedge position. During insertion, the fully inflated balloon covers the hard tip of the catheter, distributing pressure forces evenly across a broad area of the endocardium.

6.2.4.4. Percutaneous transducers. An example of a percutaneous blood pressure transducer is shown in Figure 6.26. It shows a transducer connected to a hypodermic needle that has been placed in a vessel of the arm. The three-way stopcock dome permits flushing of the needle, administering of drugs, and withdrawing of blood samples. This transducer can measure arterial or venous pressures, or the pressures of other physiological fluids, by direct attachment to a needle at the point of measurement. It can be used with a continuously self-flushing system without degradation of signal. The transparent plastic dome permits observation of air-bubble formation and consequent ejection. It is designed for use with a portable blood pressure monitor, which provides bridge excitation, balancing, and amplification. The meter scale is calibrated directly into millimeters of mercury. This transducer also has the advantage that it can be connected to a standard intravenous infusion bottle.

6.2.4.5. Implantable transducers. Figure 6.27 shows a type of transducer that can be implanted into the wall of a blood vessel or into the wall of the heart itself. This transducer is particularly useful for long-term investigations in animals.

The transducer's body is made of titanium, which has excellent corrosion-resistance characteristics, a relatively low thermal coefficient of expansion, and a low modulus of elasticity, which results in greater strain per unit stress. Four semiconductor strain gages are bonded to the inner surface of the pressure-sensing diaphragm. Transducers of this type come in a number of sizes (from 3 to 7 mm in diameter) for blood pressure measurement. A popular size is 4.5 mm in diameter. Larger sizes are available for pleural pressure. The thickness of the body is 1.2 to 1.3 mm in the various models.

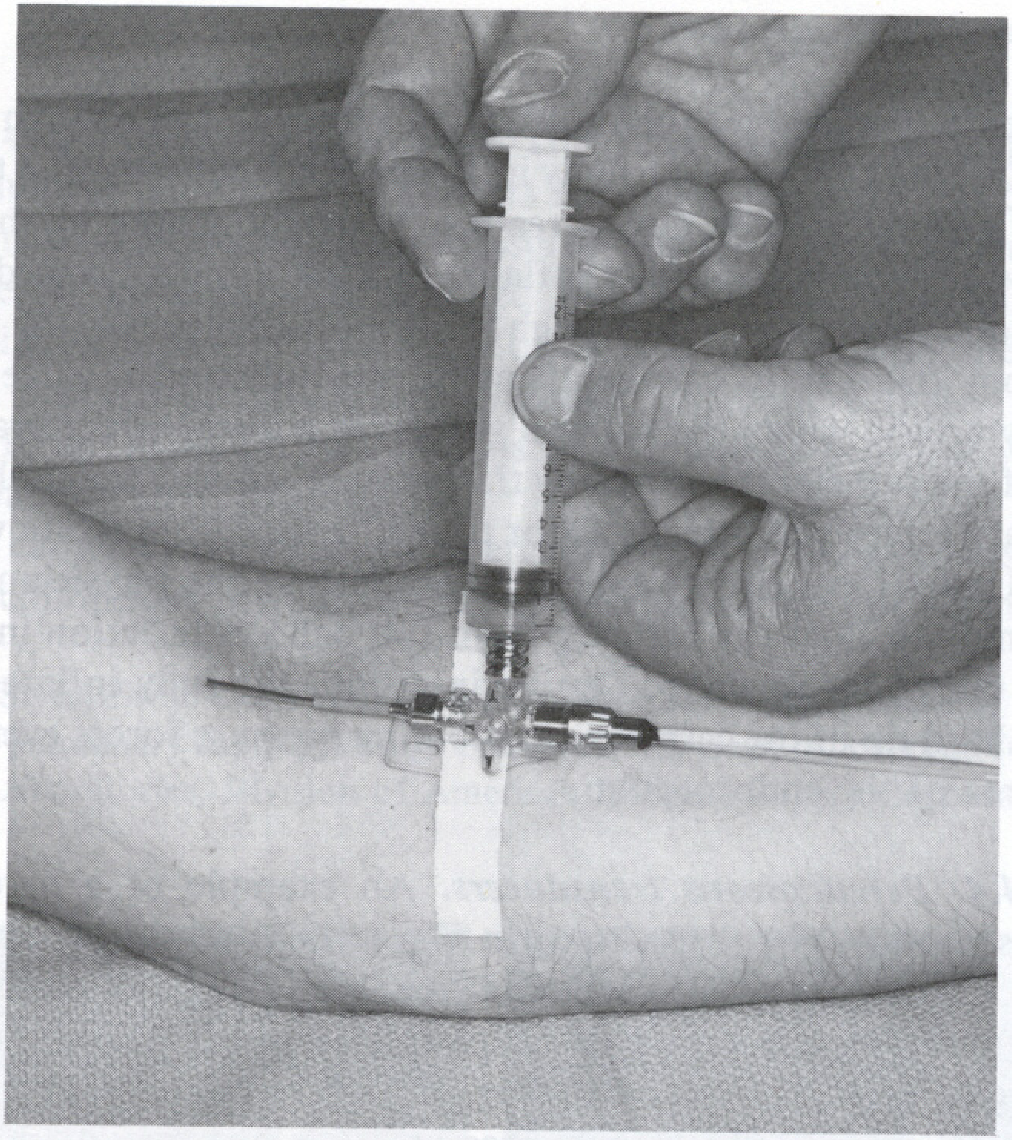

Figure 6.26. Percutaneous blood pressure measurement. Transducer in arm with three-way stopclock dome for administering drugs and withdrawing blood samples. (Courtesy of Gould Inc., Measurement Systems Division, Oxnard, CA.)

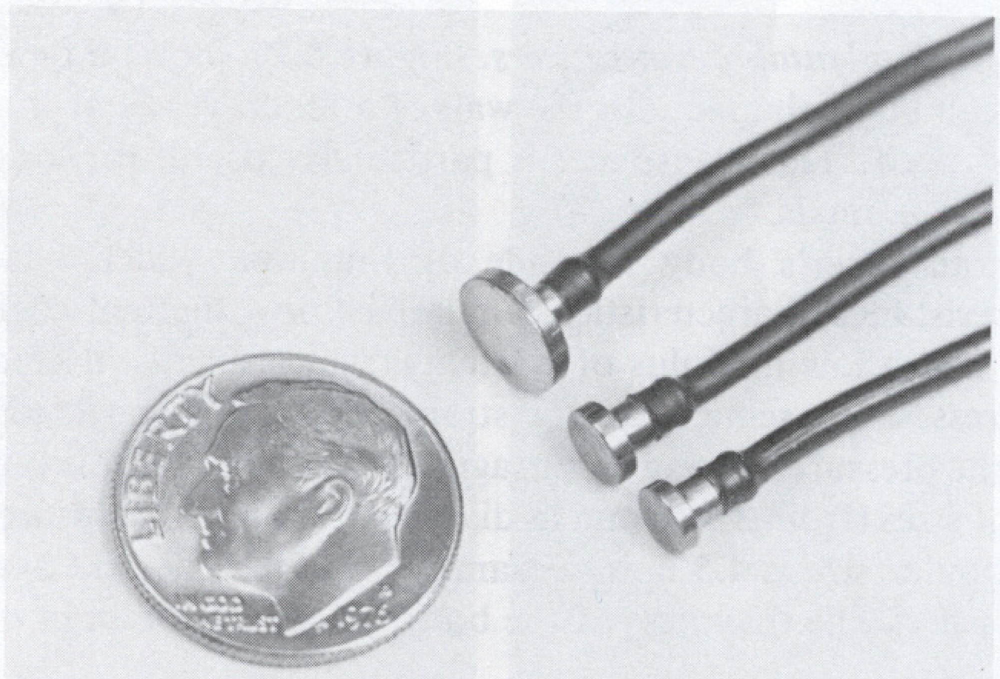

Figure 6.27. Implantable pressure transducer. (Courtesy of Konigsberg Instruments, Pasadena, CA.)

The four semiconductors are connected in bridge fashion as shown in Figure 6.19. As blood pressure increases on the diaphragm, the inner surface is stressed. The strain gages are located so that two of them are strained in tension while two are in compression. When the bridge is excited, an output voltage proportional to the blood pressure can be obtained.

Additional resistors, connected externally to the bridge, provide temperature compensation, although these bridges are not extremely sensitive to temperature. Since they operate in the bloodstream at a fairly constant 37 °C, the temperature effects are not serious.

These transducers can be excited with ac or dc and easily lend themselves to telemetry application. In service, they have proven very reliable. Cases of chronic implants (in excess of 2 years) have been reported with no detrimental effect on the animal, the gage, or the wires. The wires are usually insulated with a plastic compound, polyvinylchloride, which is fairly impervious to body fluids.

There are many examples of the use of this type of transducer in animal research, including the implantation in both ventricles of the heart, the aorta, the carotid artery, and the femoral artery. In addition to blood pressures, they have also been used for measuring abdominal, esophageal, thoracic, intrauterine and intracranial pressures.

To implant a transducer in an artery, a longitudinal incision is made; the transducer is inserted with its housing in intimate contact with the arterial walls. The wound is closed with interrupted sutures. For cardiac implants, a stab wound in the ventricle permits ready insertion, with the transducer placed free of both the myocardium and (in the left ventricle) the chordae tendonae. A technique used for long-term studies of the blood pressure in the aorta is to insert the transducer from the opposite side and use a small intercostal artery to bring the wire through. This creates a

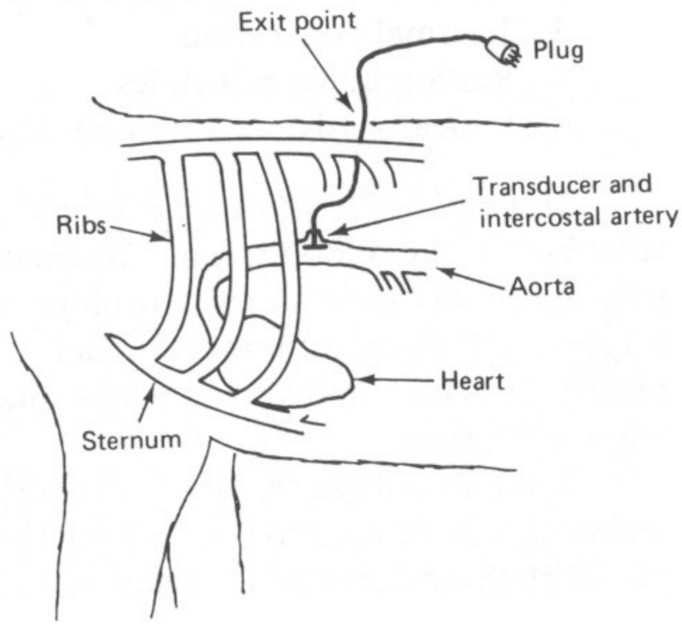

Figure 6.28. Transducer implanted in the aorta.

stronger bind in active animals. The wire is held to the artery by a purse-string suture. Figure 6.28 shows such a preparation. In this case the plug was inserted into a biotelemetry transmitter so that the blood pressure data could be received remotely. The use of these transducers and telemetry have been useful in gathering information on exercise, the effect of drugs and extreme environments, and acceleration and impact studies (see Chapter 12).