Challenges in medical measurements

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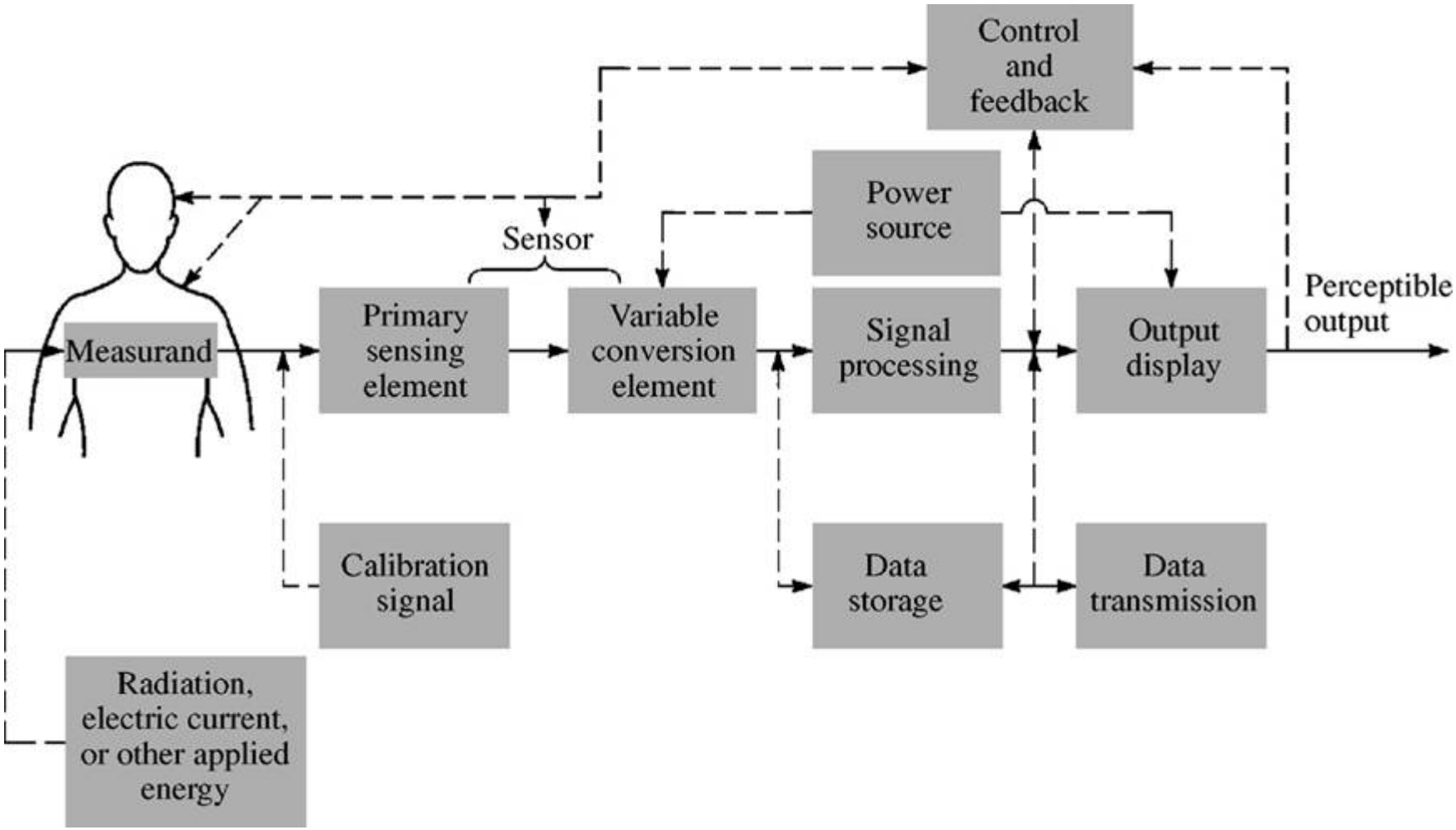


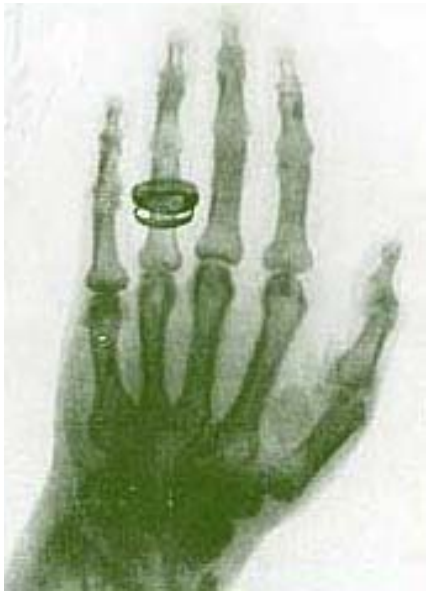
Generalized instrumentation system The sensor converts energy or information from the measurand to another form (usually electric). This signal is then processed and displayed so that humans can perceive the information. Elements and connections shown by dashed lines are optional for some applications.

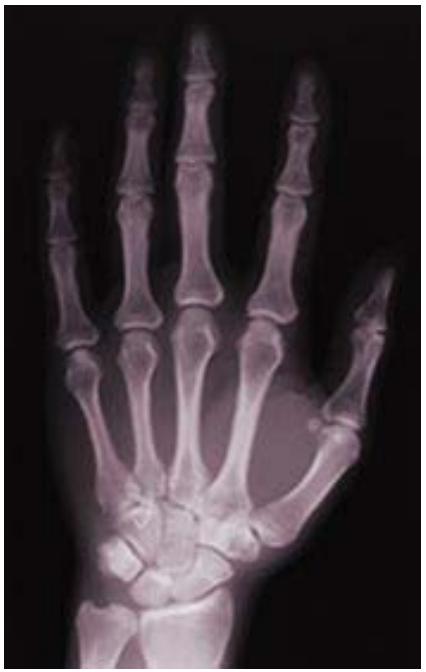
Historical background

- 1816 stethoscope
- 1850 clinical thermometers
- 1850 ophthalmoscopes
- 1857 laryngoscopes
- 1860 scopes for the rectum and vagina
- 1877 cystocopes for the urinary bladder
- 1895 x-rays
- 1896 sphygmomanometers
- 1901 ECG devices
- 1918 arthroscopes
- 1927 iron lung
- 1929 cardiac catheter
- 1929 EEG instruments
- 1931 Electrosurgery
- 1944 artificial kidney
- 1950s fiber optic imaging bundles
- 1951 cardiopulmonary bypass unit
- 1951 PET
- 1952 mechanical heart valves

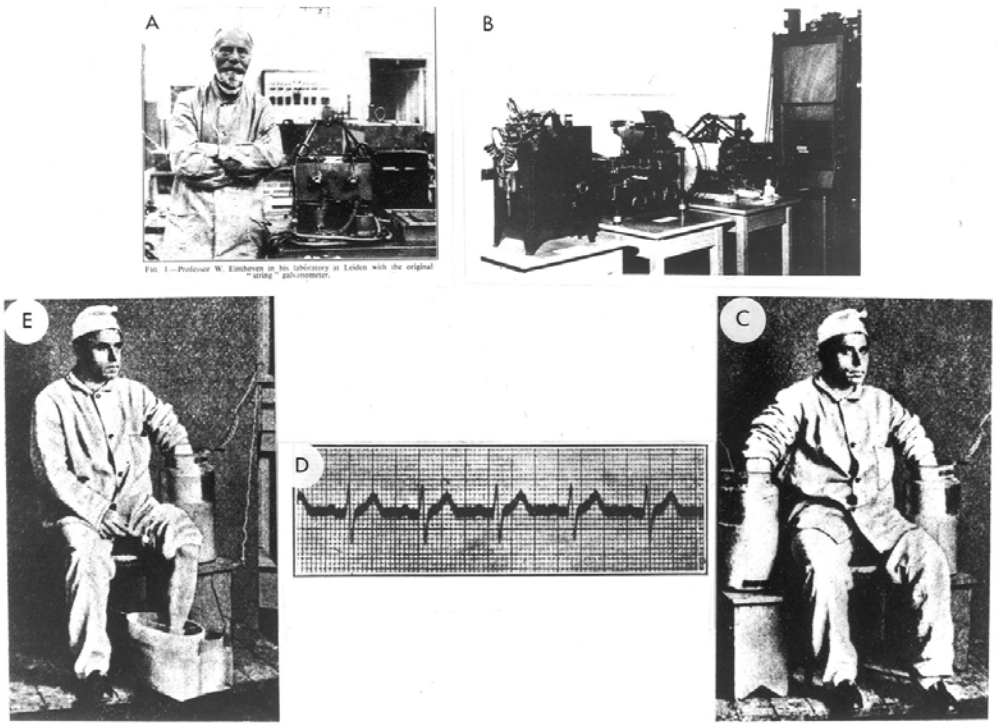
- 1954 donor-organ transplants of the kidney
- 1957 synthetic arterial grafts
- 1959 artificial kidney chronic use
- 1959 implantable pacemakers
- 1960 cemented total artificial hips
- 1960 laser
- 1961 intra-aortic balloon pump
- 1963 donor-organ transplants of the liver
- 1963 pulsatile ventricular assist devices
- 1964 artificial kidney home use
- 1965 xenograft bioprosthetic heart valves
- 1967 donor-organ transplants of the heart
- 1968 balloon angioplasty
- 1968 ultrasonography
- 1969 artificial hearts
- 1971 CT
- 1980s MRI
- 1983 laparoscopic appendectomy
- 1987 laparoscopic cholecystectomy
- 1990s donor-organ transplants of the intestines & pancreas

- Important historical developments:
- In 1896 Wilhelm Röntgen discovered something that would prove to be one of the major medical breakthroughs of the twentieth century—the x-ray. Röntgen's x-ray was a major medical breakthrough. For the first time in human history it gave medical personnel a means of seeing inside the body without having to resort to surgical procedures. The use of x-rays spread quickly around the globe. Röntgen received the Nobel Prize in Physics for his discovery in 1901.

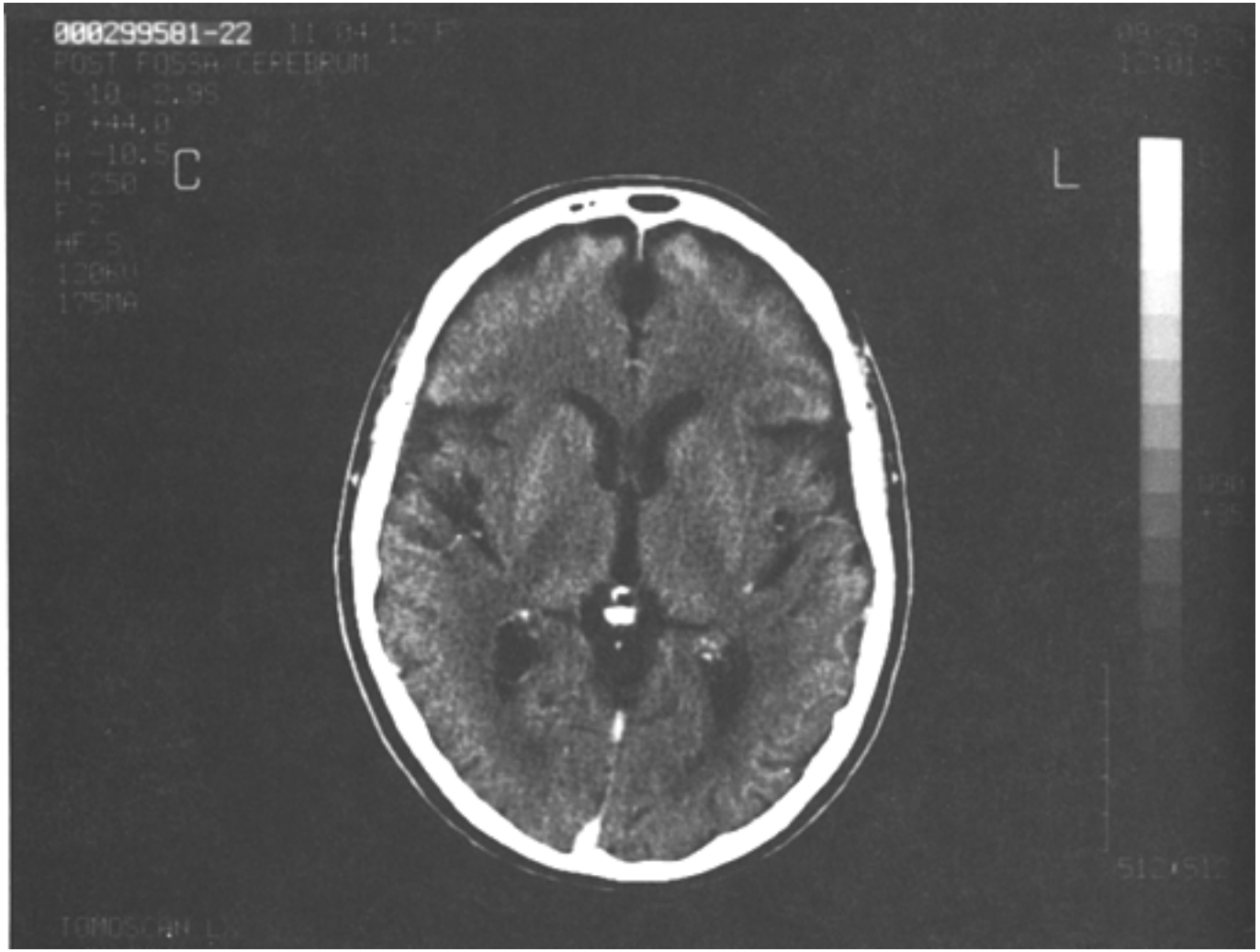




- Important historical developments:
- Beginning in 1901, Einthoven completed a series of prototypes of a string galvanometer. This device used a very thin filament of conductive wire passing between very strong electromagnets. When a current passed through the filament, the electromagnetic field would cause the string to move. A light shining on the string would cast a shadow on a moving roll of photographic paper, thus forming a continuous curve showing the movement of the string. Thus the electrocardiogram below.

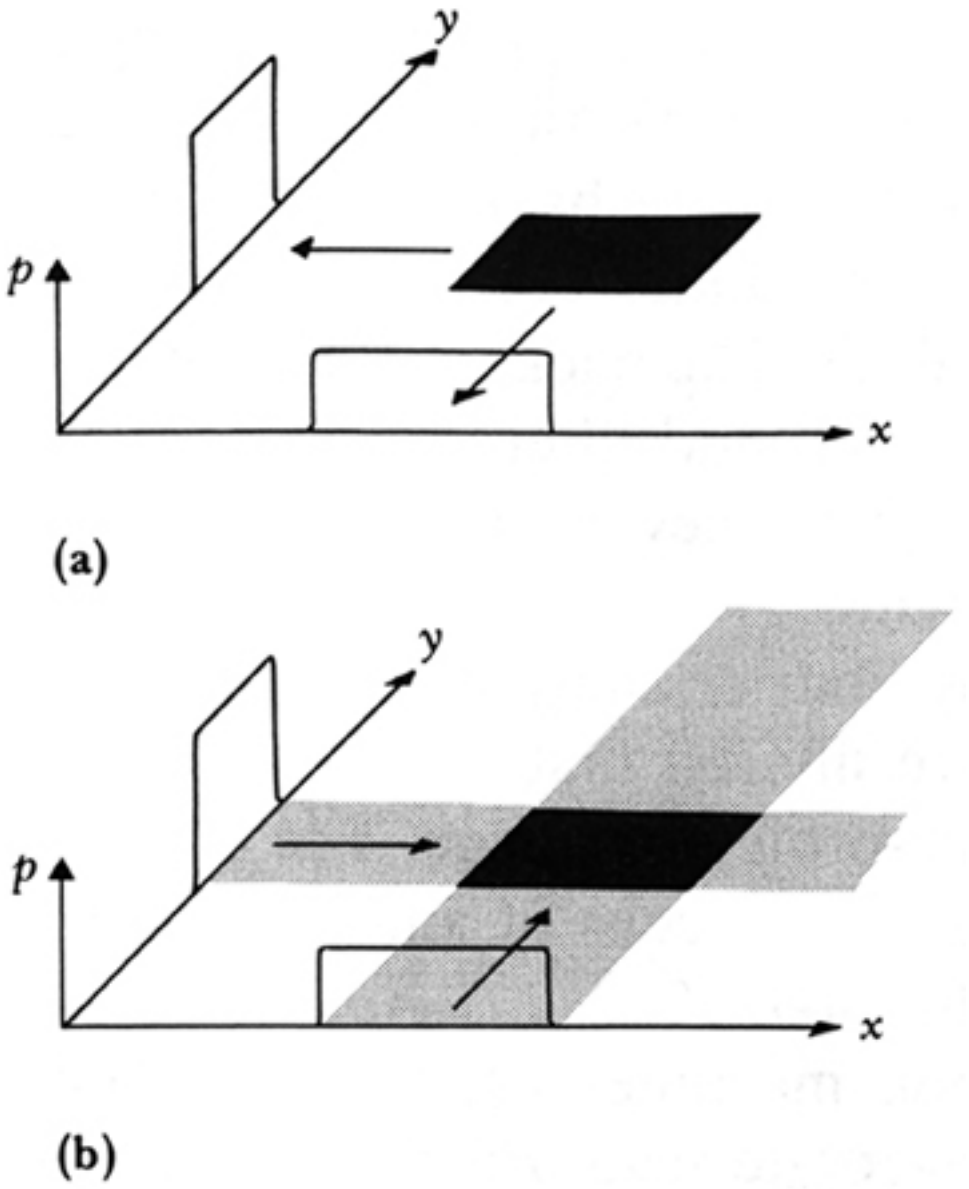


Important historical developments:

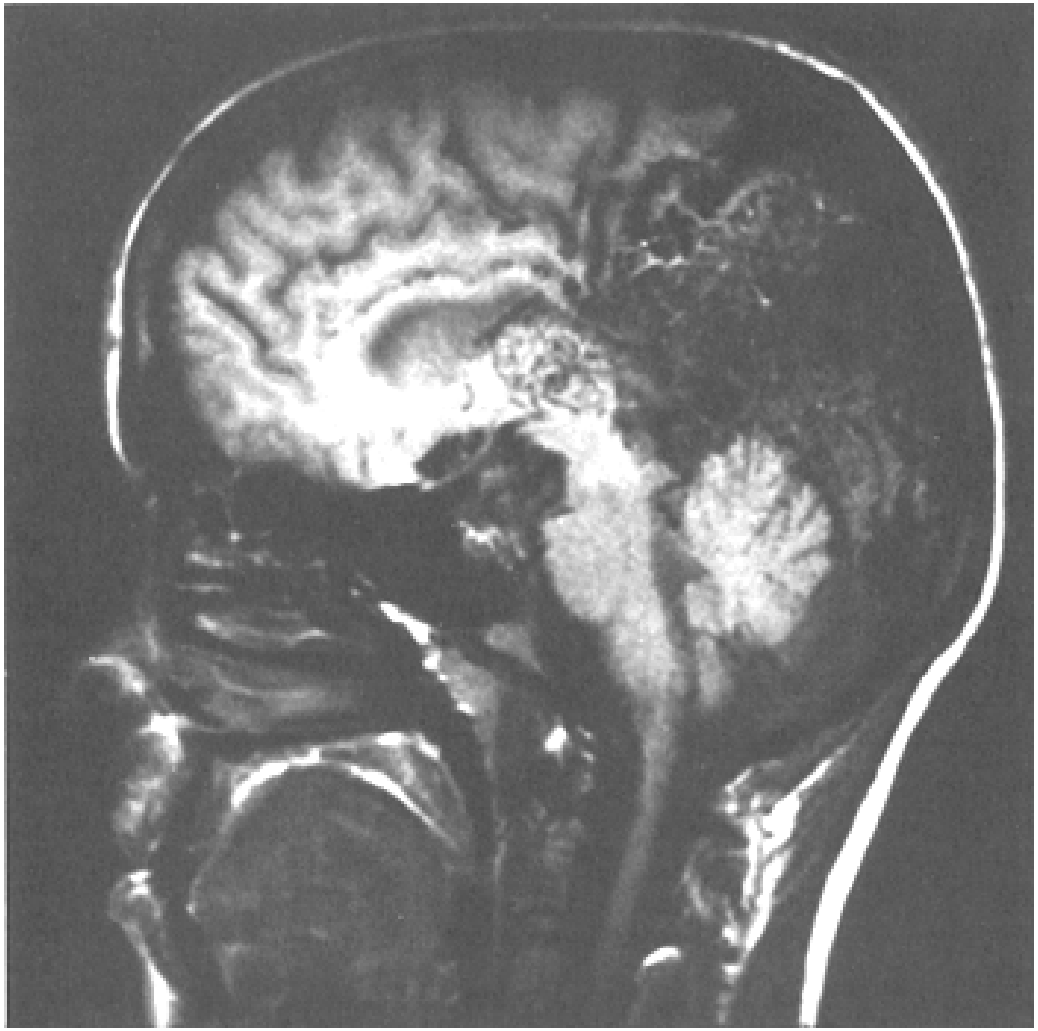


512 × 512 pixel CT image of the brain Note that the increased number of pixels yields improved images

How does CT work?
Back projection (a) Projections of this object in the two directions normal to the *x* and *y* axes are measured. (b) These projection data are projected back into the image plane. The area of intersection receives their summed intensities. It is apparent that the back-projected distribution is already a crude representation of the imaged object.

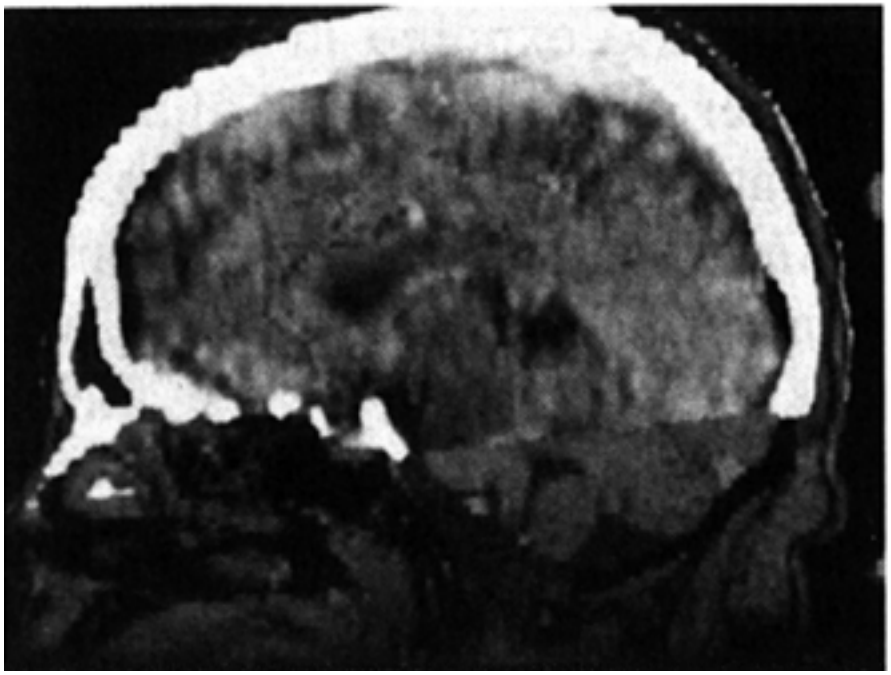


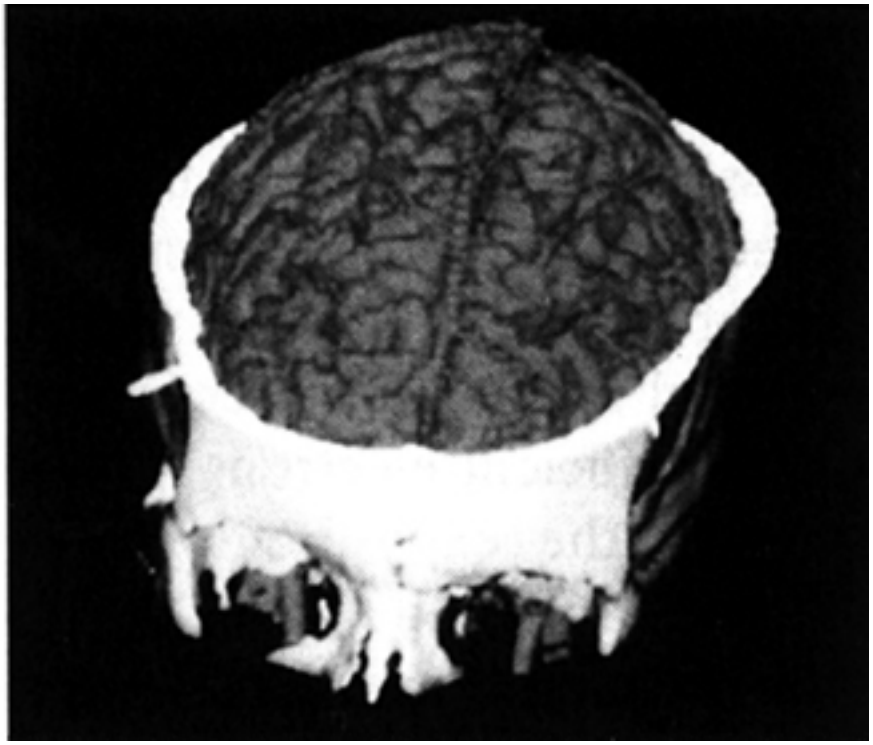
Important historical developments:



MRI image of the head

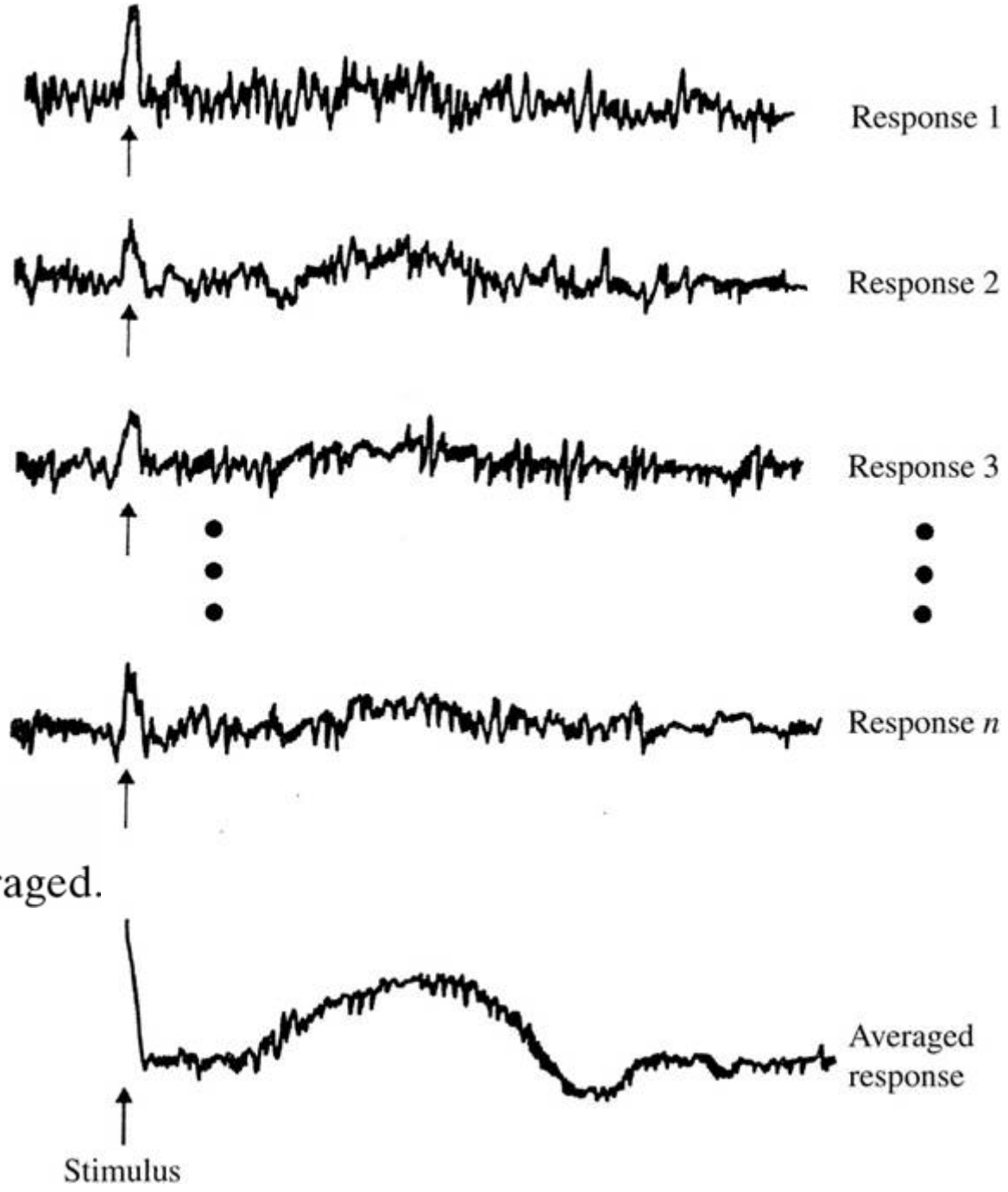
Important historical developments:





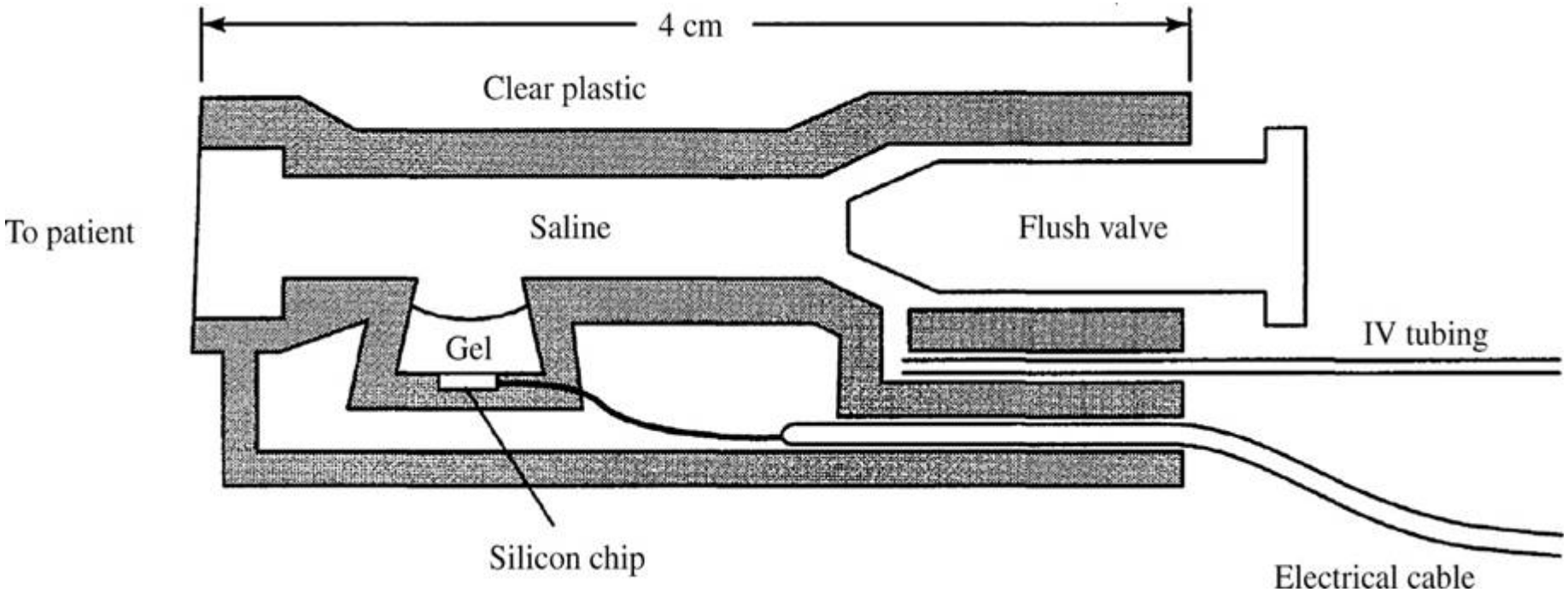
Images of the skull taken using CT and images of the brain taken with MRI, fused into composite images.

Signal-averaging technique for improving the SNR in signals that are repetitive or respond to a known stimulus.



$$10 = \sqrt{n}$$

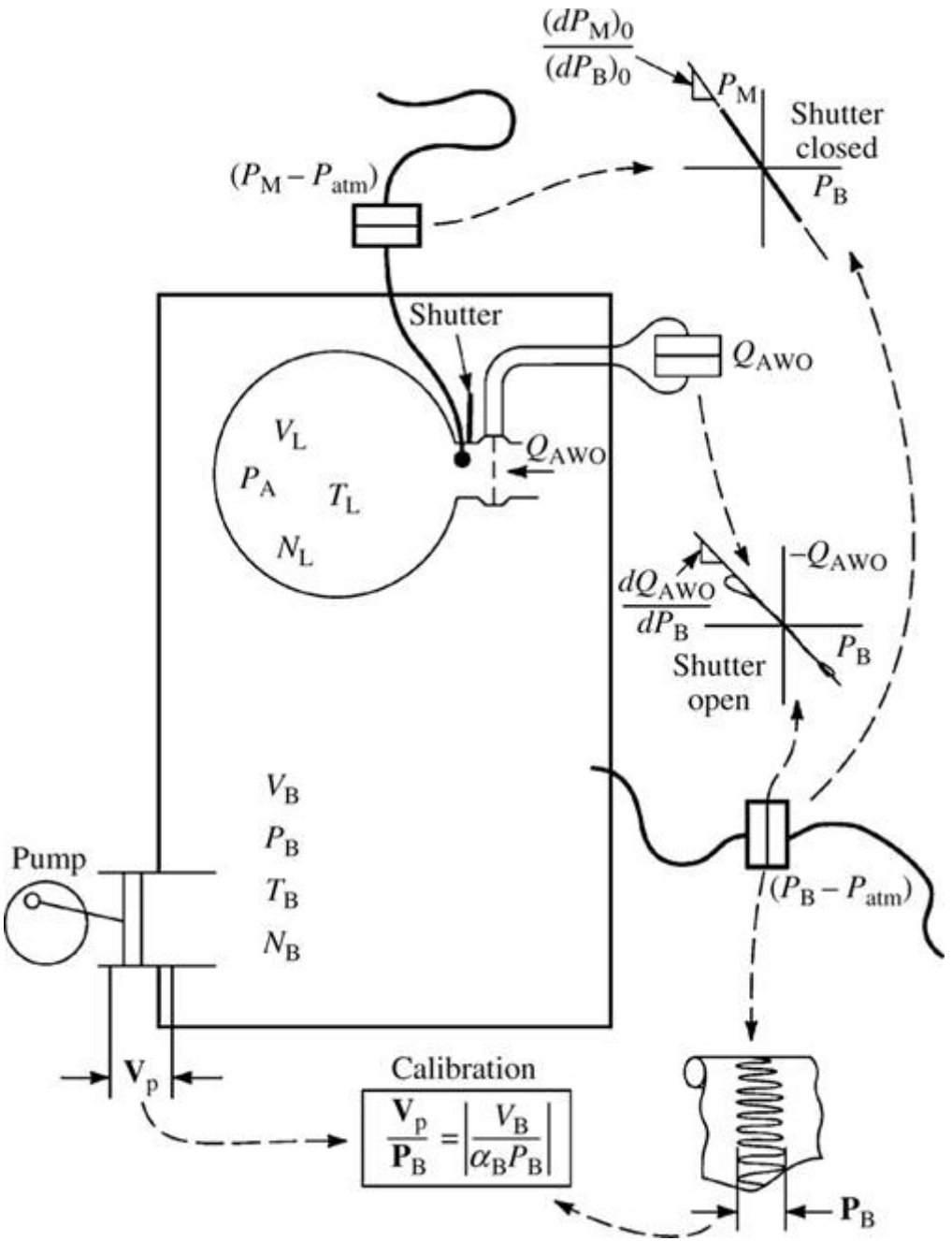
$$n = (10)^2 = 100 \text{ samples averaged.}$$

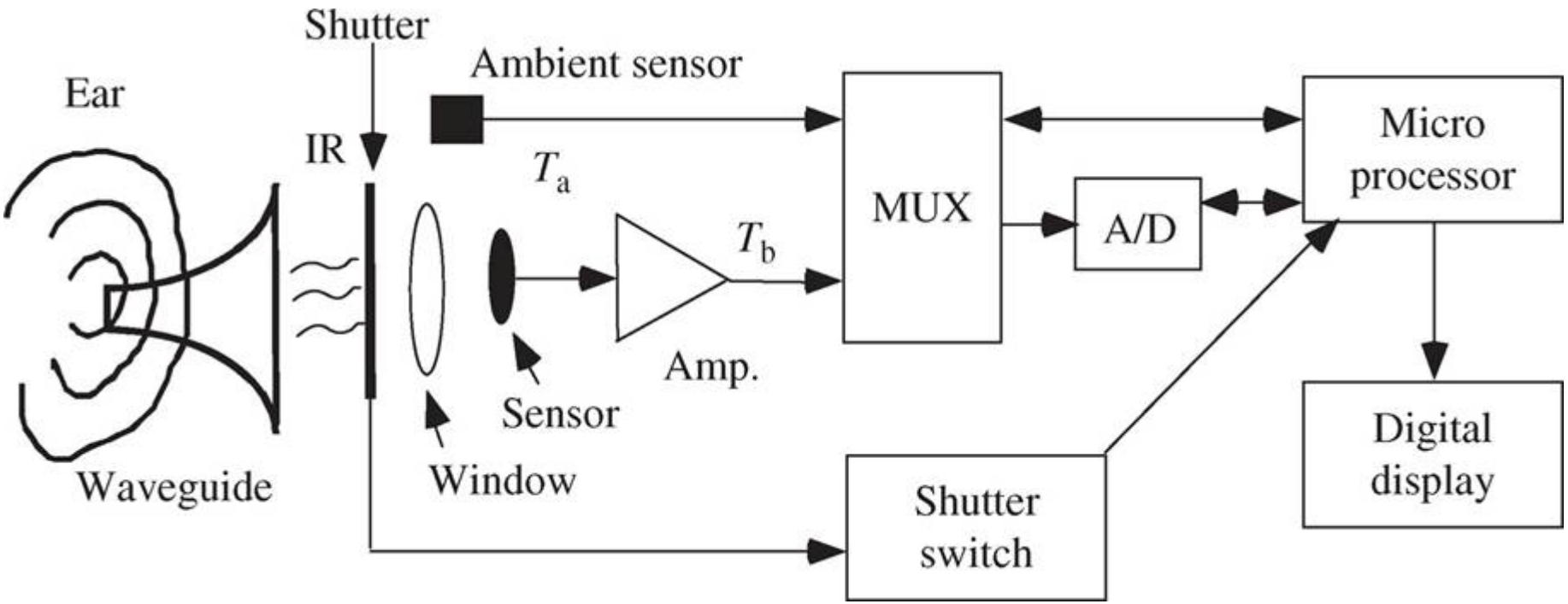


Isolation in a disposable blood-pressure sensor. Disposable blood pressure sensors are made of clear plastic so air bubbles are easily seen. Saline flows from an intravenous (IV) bag through the clear IV tubing and the sensor to the patient. This flushes blood out of the tip of the indwelling catheter to prevent clotting. A lever can open or close the flush valve. The silicon chip has a silicon diaphragm with a four-resistor Wheatstone bridge diffused into it. Its electrical connections are protected from the saline by a compliant silicone elastomer gel, which also provides electrical isolation. This prevents electric shock from the sensor to the patient and prevents destructive currents during defibrillation from the patient to the silicon chip.

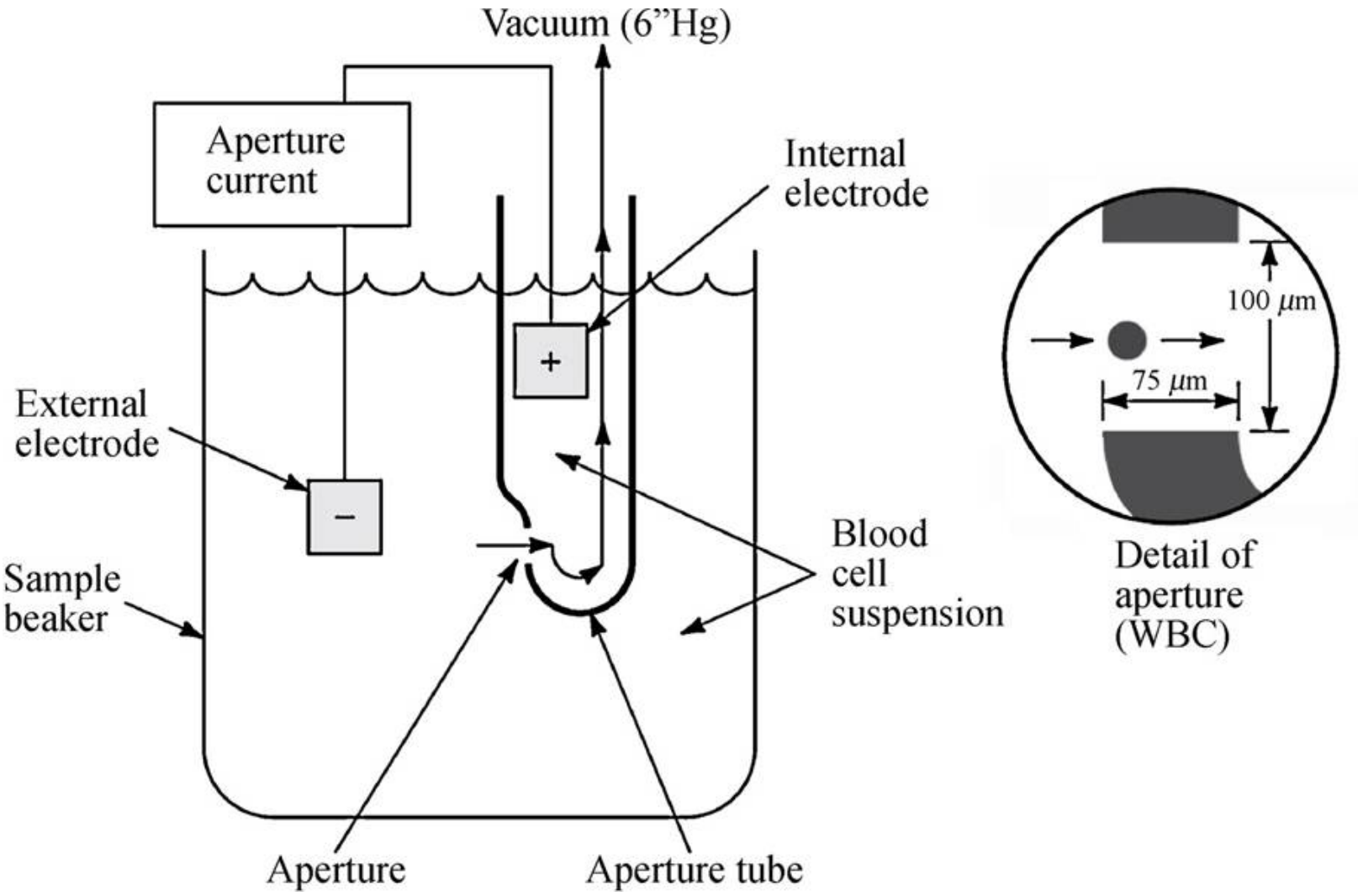
To measure pressure inside the lung, we cannot insert a pressure sensor or even a tube with an external pressure sensor.

We solve the problem by putting the patient in a box. The patient blows hard against the closed shutter. The decreased lung volume yields an increased box volume and a decreased box pressure. Thus the lung pressure can be calculated from the box pressure. Then the patient blows through a open shutter. Airway resistance then equals lung pressure divided by air flow. $R = P/Q$.





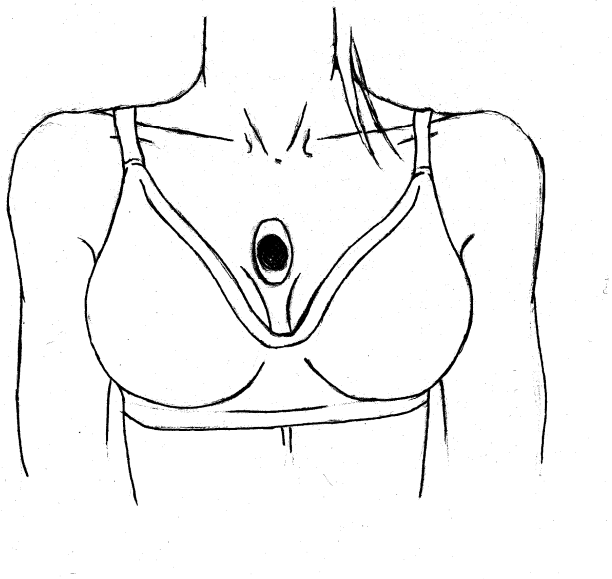
The infrared thermometer opens a shutter to expose the sensor to radiation from the tympanic membrane. From J. G. Webster, Ed., *Bioinstrumentation*, New York: John Wiley & Sons, 2004.

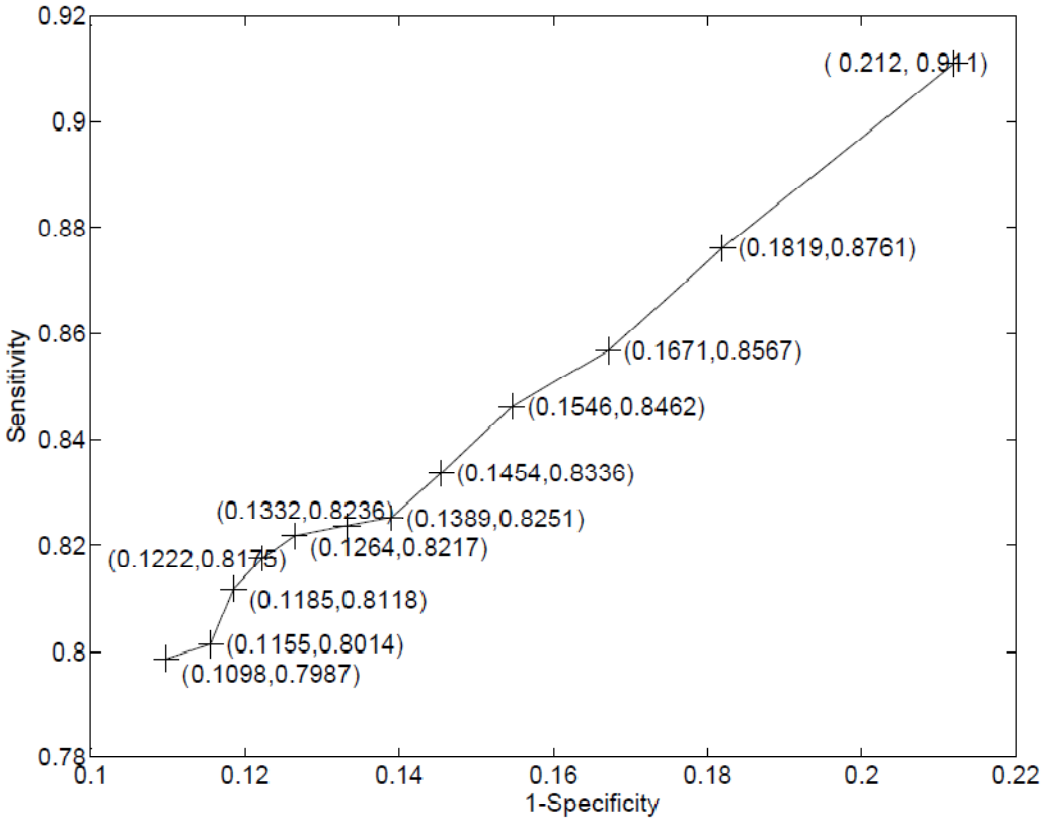


A vacuum pulls diluted blood through a small aperture. Electrodes on each side of the aperture permit measuring the change in impedance caused by the insulating red blood cell. The Coulter counter measures number of cells and also their volume distribution.

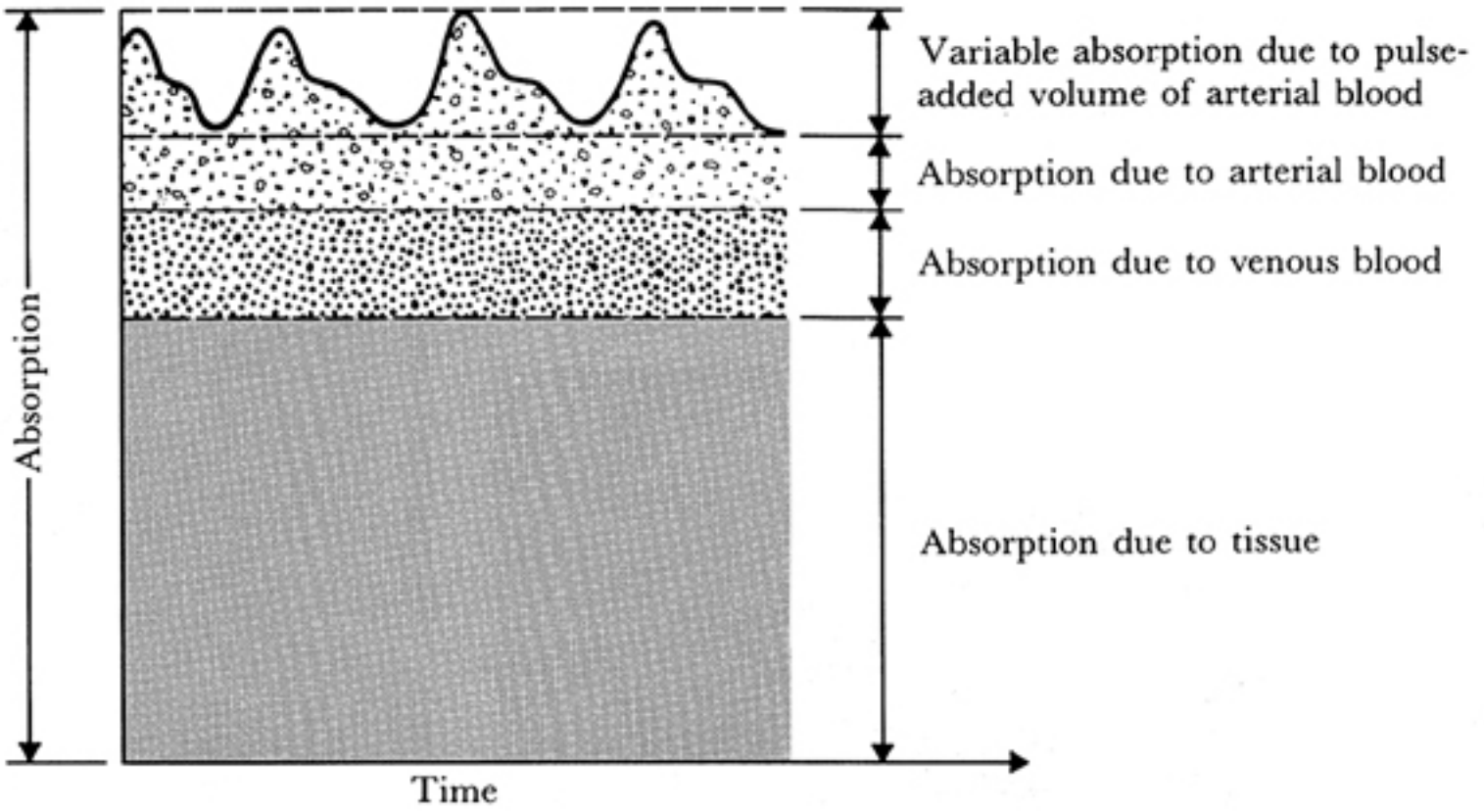
How do sensitivity and specificity relate to the receiver operating characteristic?

$$\text{Sensitivity} = \frac{TP}{TP + FN} = \frac{45}{45 + 1}$$

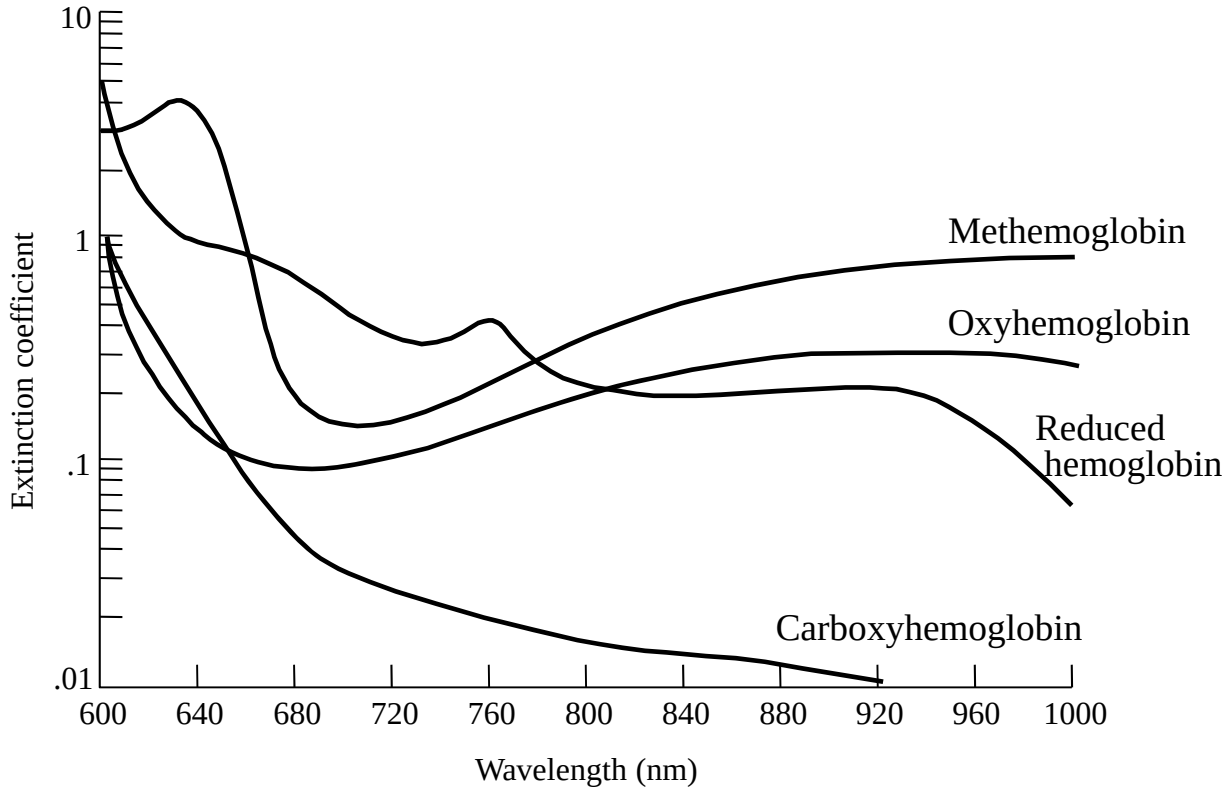




Important historical development: Noninvasive measurement of tissue blood oxygen saturation



The pulse oximeter analyzes the light absorption at two wavelengths of only the pulse-added volume of oxygenated arterial blood.



Absorptivities (extinction coefficients) in L/(mmol·cm) of the four most common hemoglobin species at the wavelengths of interest in pulse oximetry. The largest difference between oxyhemoglobin and reduced hemoglobin is at 940 nm.

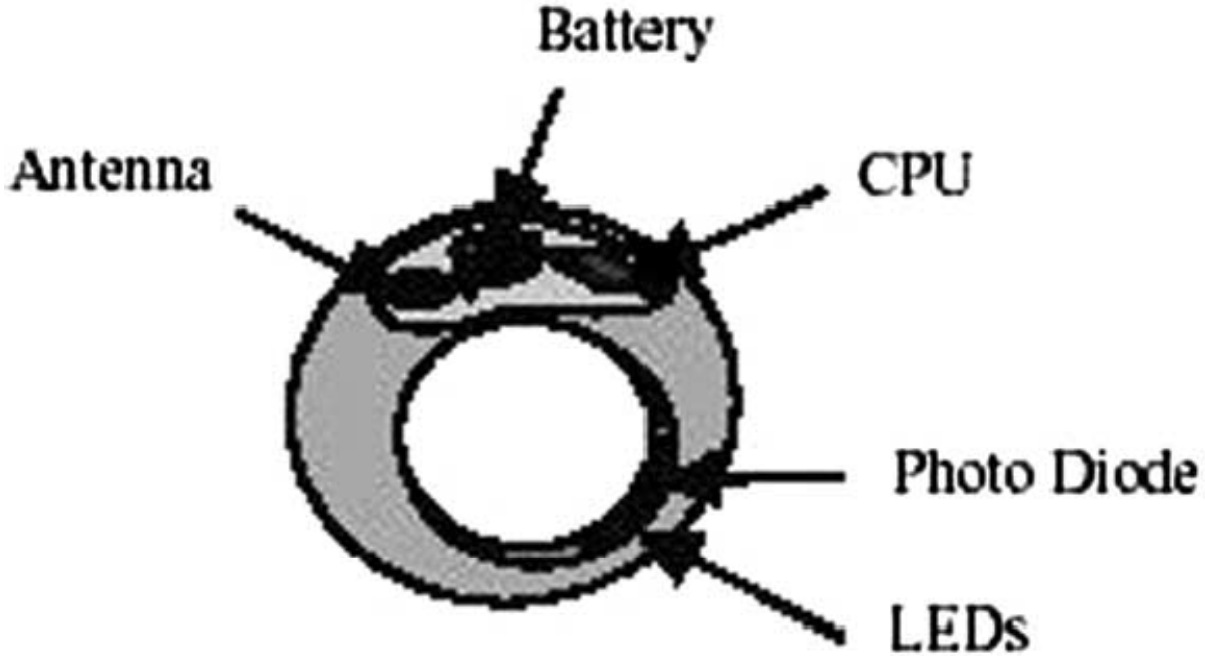
Should we continuously measure tissue blood oxygen saturation in the home and transmit it to the hospital?

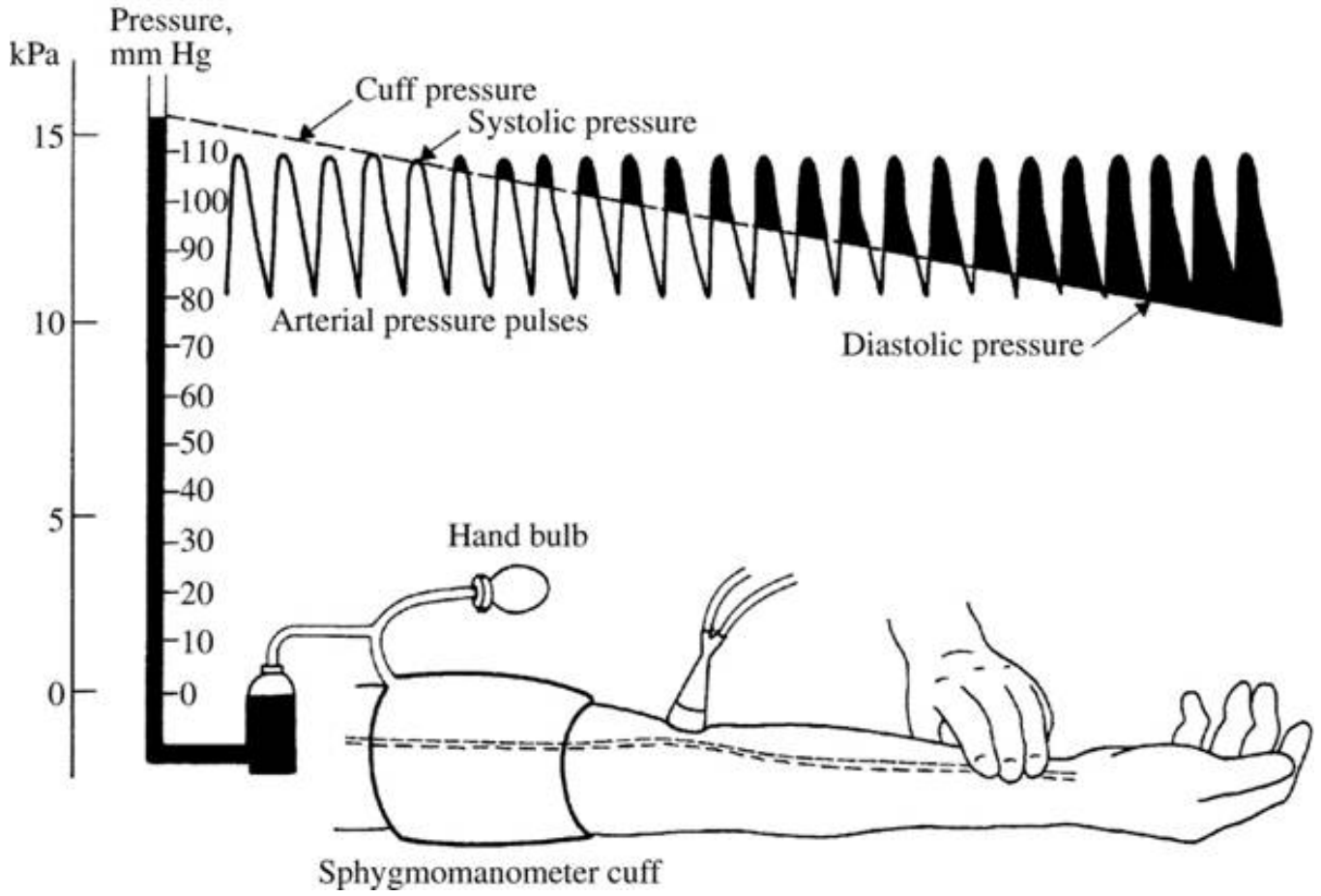
No, because most people would not wear it.

Motion artifacts are too great for accuracy.

By the time it decreases from its usual 98%, something else is very bad.

There are research reports that suggest that a patient wear a ring to measure finger oxygenation. LEDs would shine light into the finger and a photodiode would receive it and transmit oxygen saturation to a receiving station elsewhere on the body. However the motion artifacts would be bad. By the time oxygen saturation decreased from its usual 98% the heart and lungs would be in very bad condition.

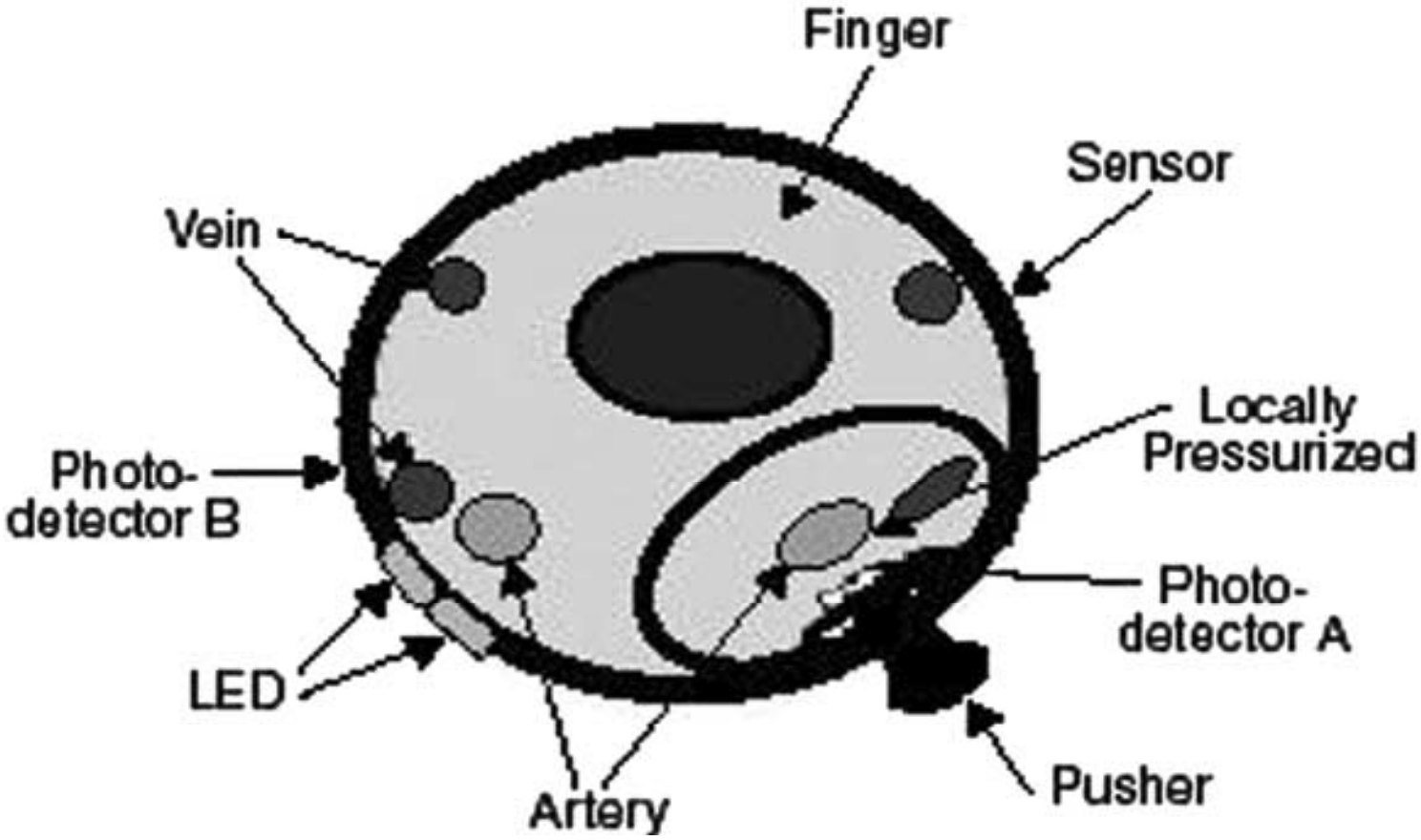




Typical indirect blood-pressure measurement system The sphygmomanometer cuff is inflated by a hand bulb to pressure above the systolic level. Pressure is then slowly released, and blood flow under the cuff is monitored by a microphone or stethoscope placed over a downstream artery. The first Korotkoff sound detected indicated systolic pressure, whereas the transition from muffling to silence brackets diastolic pressure.

Should we continuously measure blood pressure in the home and transmit it to the hospital?

Researchers have suggested that patients would carefully adjust a pusher to compress a finger artery half way in order to continuously monitor blood pressure. However the adjustment is difficult and any ring movement would require readjustment of the pusher. So no patient would use this.



There are research reports about wearable shirts containing medical sensors that continuously monitor cardiac rhythm, blood pressure, respiration, etc.
Would you wear this special shirt day and night? How often would you wash it? Would you remove the sensors for washing? Would you attach the sensors to your body?
I do not think the cost and difficulty justify a shirt with sensors.

(a)

(b)

How do we best measure cardiac rhythm disease? Should we monitor rhythm continuously in the home?

If you have a heart attack and become a patient in a cardiac care ward, you will normally have telemetry attached so that if your heart stops, nurses can rescue you within a minute. So that is good.

We have the ability to monitor cardiac rhythm continuously at home at great cost.

But if you have a heart attack at home, by the time emergency medical services get there, you will be brain dead. So it is bad to monitor.

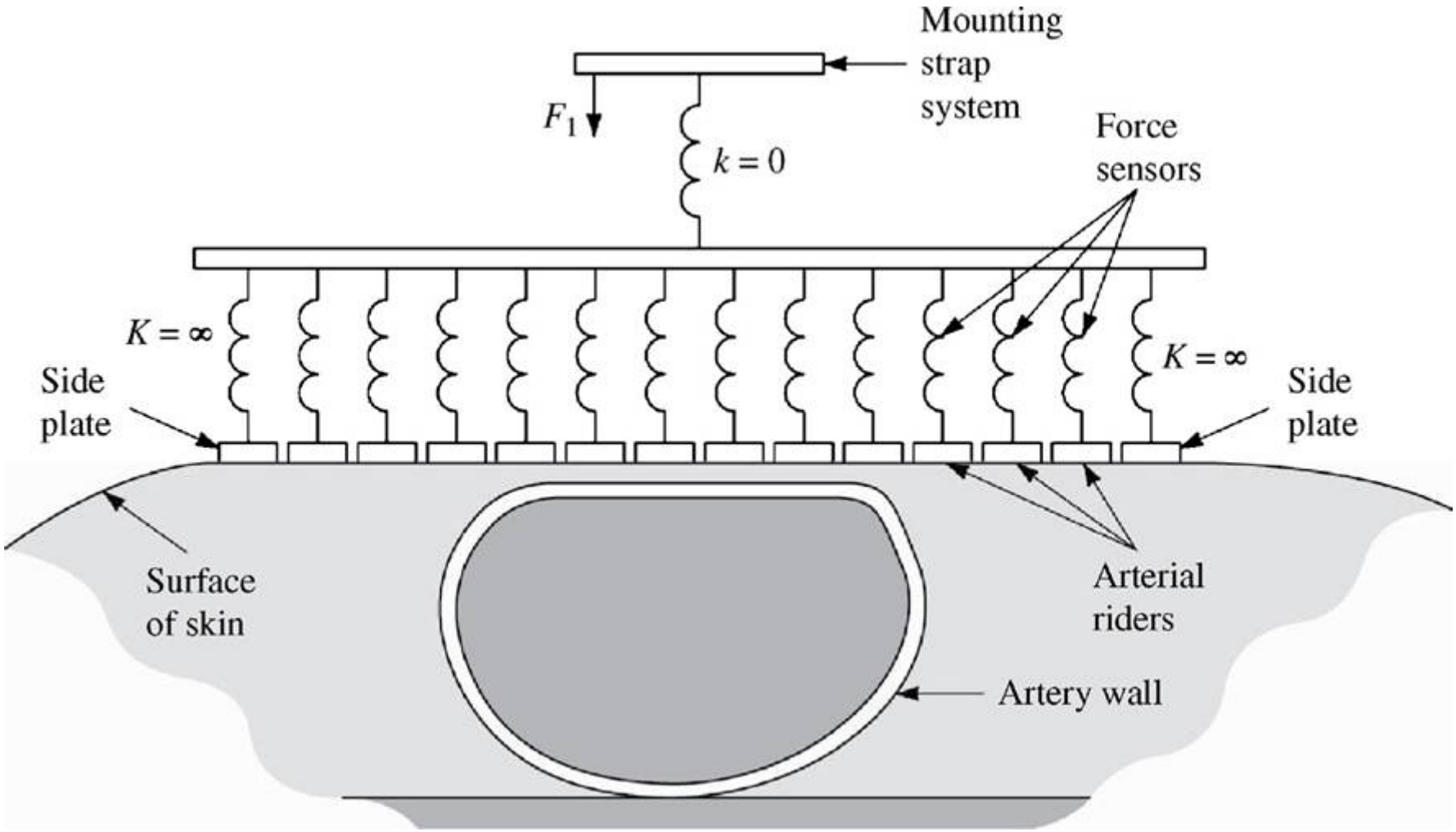
Can we minimize hospital costs by performing a sleep study in the home?

When 3% of people fall asleep, their airway muscles relax and close the airway, causing them to wake up.

At great cost, they are monitored in a sleep lab all night for respiration, blood oxygen saturation, electrocardiogram, electroencephalogram

A simple take home kit could measure respiration, blood oxygen saturation, and electrocardiogram to determine if the patient is OK or requires the costly sleep lab measurements.

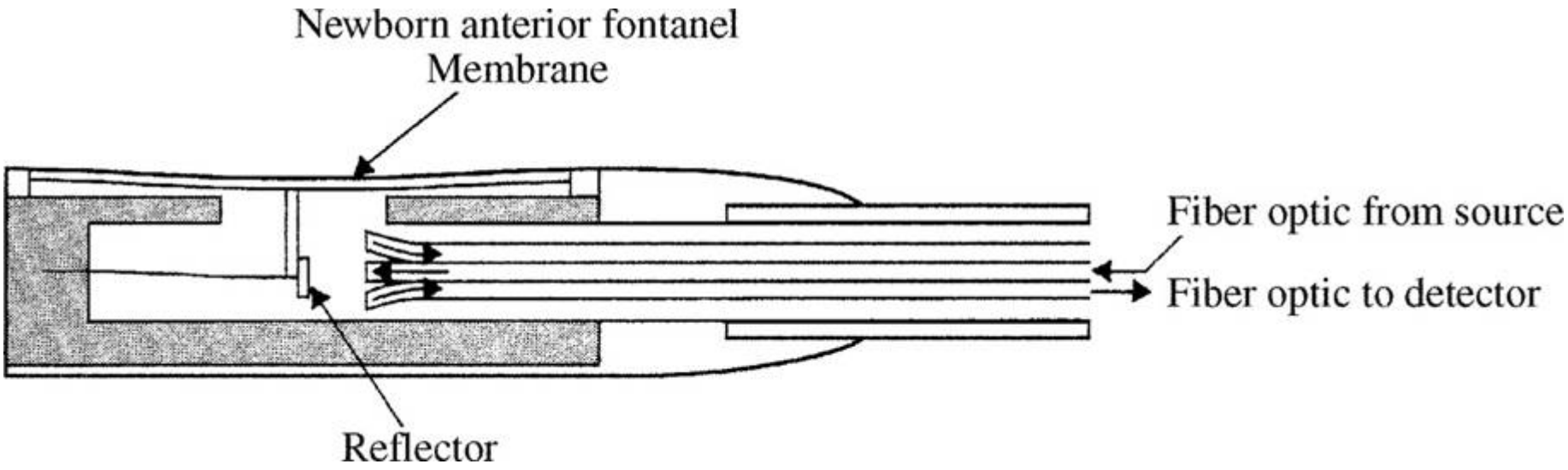
The stiffness of arteries increases with age and also with disease. Can we provide a measure of arterial stiffness to provide the cardiologist with another method of diagnosis?



Multiple-element arterial tonometer. The multiple element linear array of force sensors and arterial riders are used to position the system such that some element of the array is centered over the artery. The artery must be compressed half way so it is flaccid and has no hoop stresses.

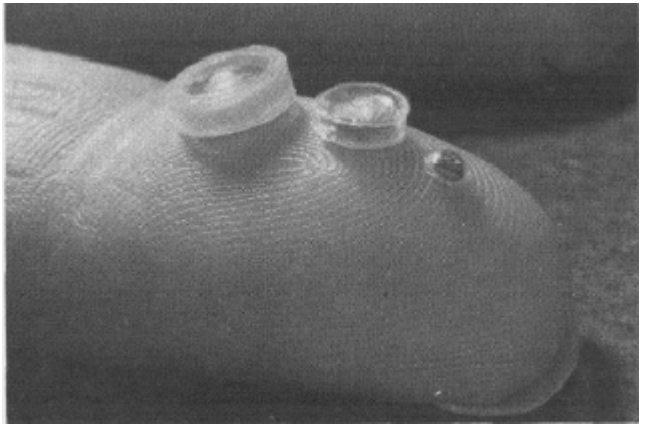
- Simplify the multisensor tonometer by using just 1 sensor
- Use ultrasonic imaging to center the sensor over the artery
- Use ultrasonic imaging to compress the artery half way
- Tap the sensor to provide a step displacement
- Record the step response
- Use signal processing to identify stiff artery (quick resonant response) or flaccid artery (slow nonresonant response)

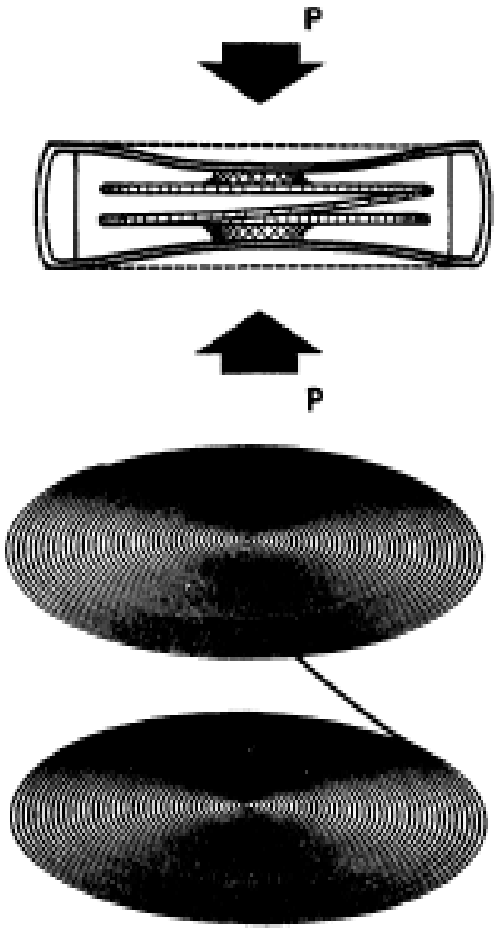
If fluid drainage from the brain is blocked, the increased pressure damages the brain. A fiber-optic pressure sensor measures intracranial pressure in the newborn.



We wish a permanently implanted pressure sensor that can be used daily to ensure future blockage does not occur.

A possible pill sized passive sensor could contain 2 spiral-wound coils that would be pushed together when the external pressure deflects the enclosure. Both the inductance and the intercoil capacitance would change, thus changing the resonant frequency. An external coil above the scalp could sweep the frequency to measure the resonant frequency, in the same way a scanner interrogates an RFID tag.



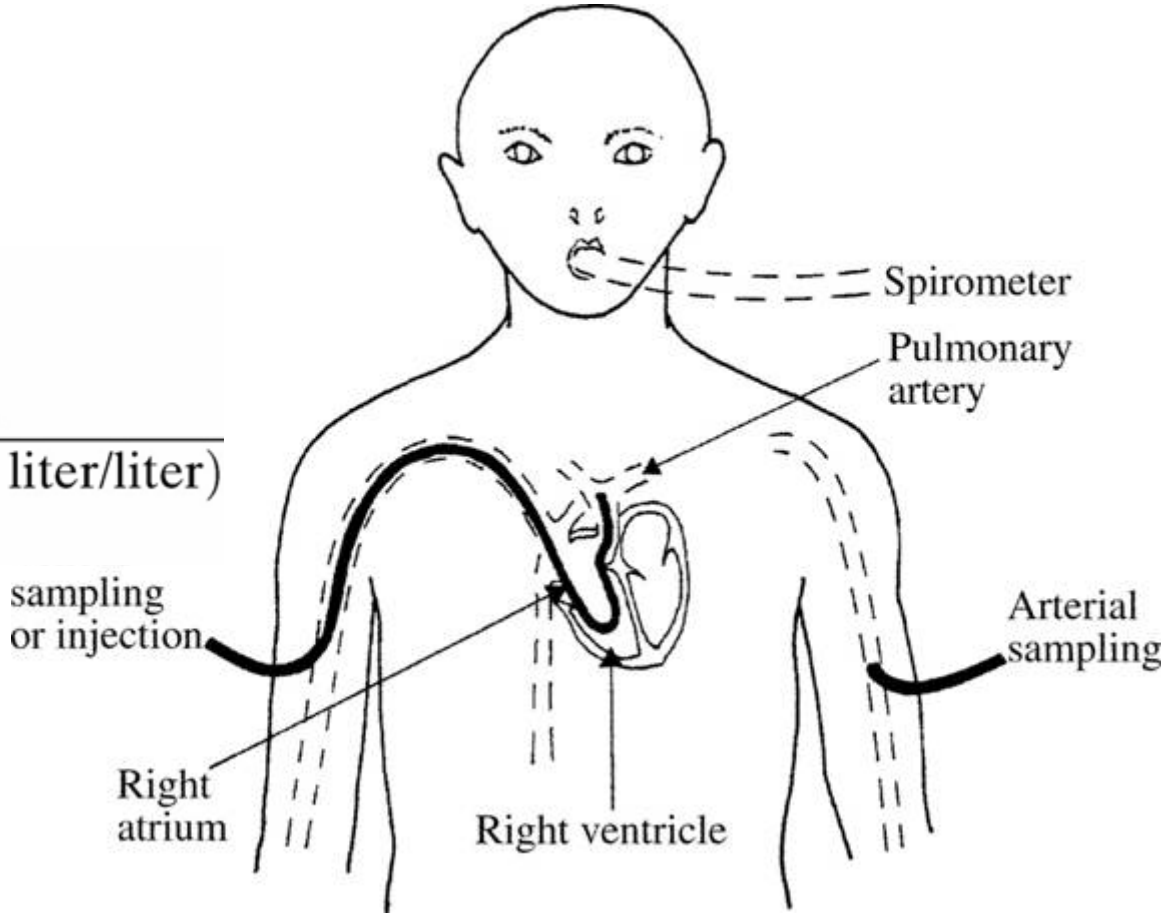


$$F = \frac{dV}{dt} = \frac{dm/dt}{\Delta C}$$

$$F = \frac{dm/dt}{C_a - C_v}$$

$$= \frac{0.25 \text{ liter/min}}{(0.20 \text{ liter/liter}) - (0.15 \text{ liter/liter})}$$

$$= 5 \text{ liters/min}$$

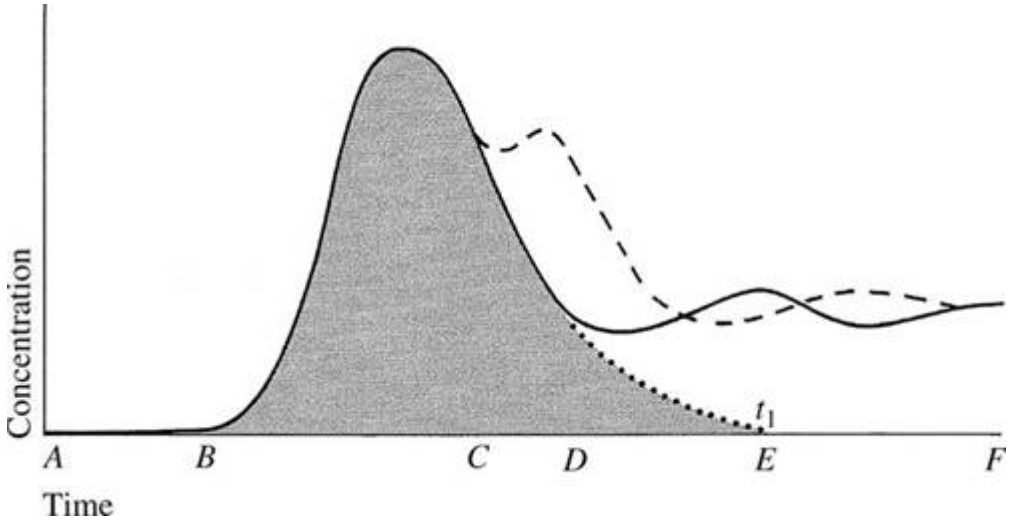


Several methods of measuring cardiac output. In the Fick method, the indicator is O2; consumption is measured by a spirometer. The arterial-venous concentration difference is measured by drawing samples through catheters placed in an artery and in the pulmonary artery. In the dye-dilution method, dye is injected into the pulmonary artery and samples are taken from an artery. In the thermodilution method, cold saline is injected into the right atrium and temperature is measured in the pulmonary artery.

$$m = \int_0^{t_1} F_i C(t)\,dt$$

$$F = \frac{m}{\int_0^{t_1} C(t)\,dt}$$

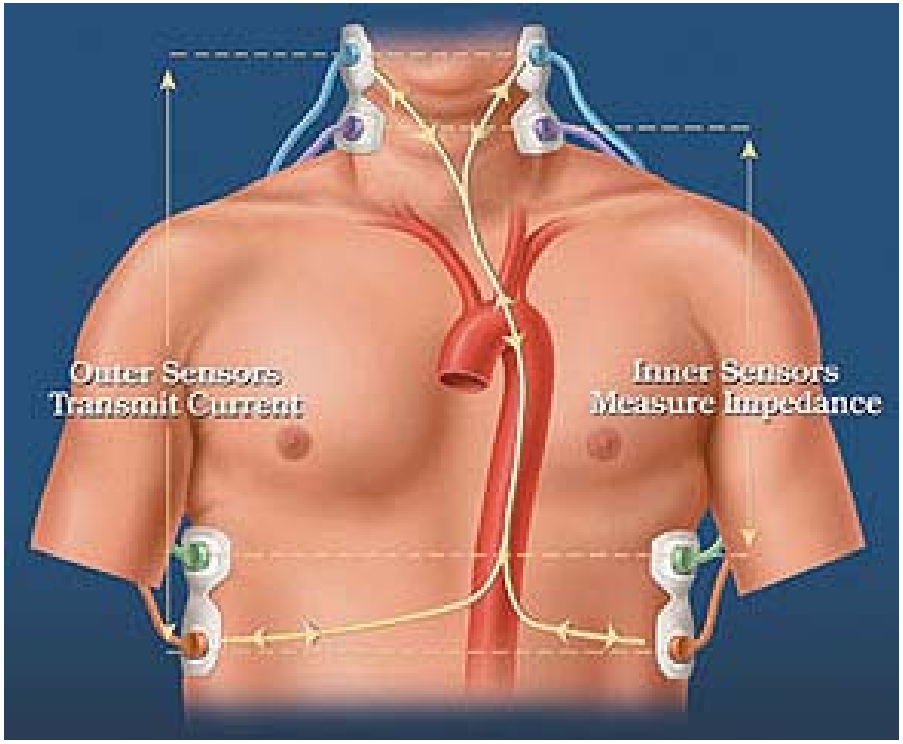
$$F = \frac{m}{\int_0^{t_1} [\Delta C(t)]\,dt}$$



$$F = \frac{Q}{\rho_b C_b \int_0^{t_1} \Delta T_b(t)\,dt} \text{ (m}^3\text{/s)}$$

Rapid-injection indicator-dilution curve. After the bolus is injected at time *A*, there is a transportation delay before the concentration begins rising at time *B*. After the peak is passed, the curve enters an exponential decay region between *C* and *D*, which would continue decaying along the dotted curve to *t*1 if there were no recirculation. However, recirculation causes a second peak at *E* before the indicator becomes thoroughly mixed in the blood at *F*. The dashed curve indicates the rapid recirculation that occurs when there is a hole between the left and right sides of the heart.

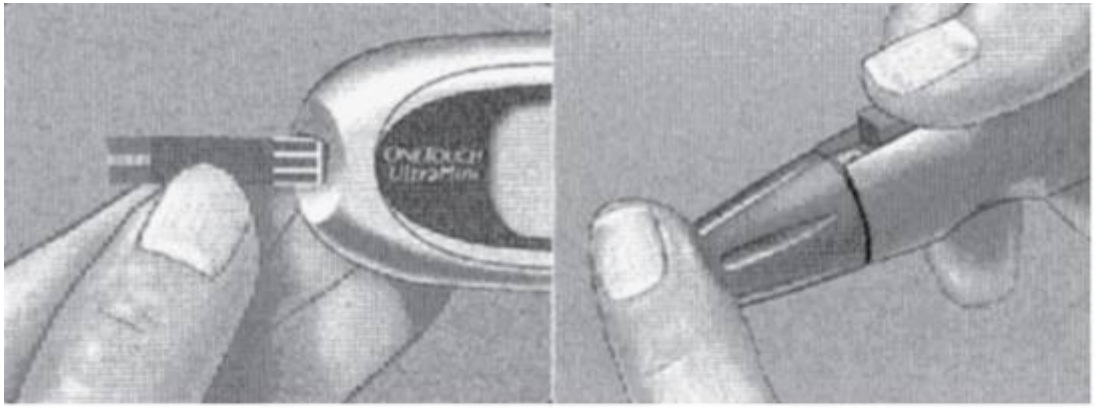
Now cardiac output can be measured noninvasively using impedance cardiography. A 50 kHz current flows from waist to neck. The current seeks the path of least resistance: the blood filled aorta. Blood volume in the aorta changes with each heartbeat. The method is not accurate enough to be used clinically. Could the accuracy be improved by placing electrodes over the left ventricle to improve spatial sensitivity?

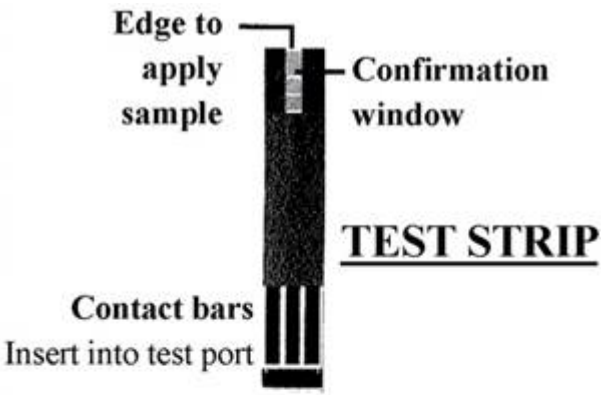


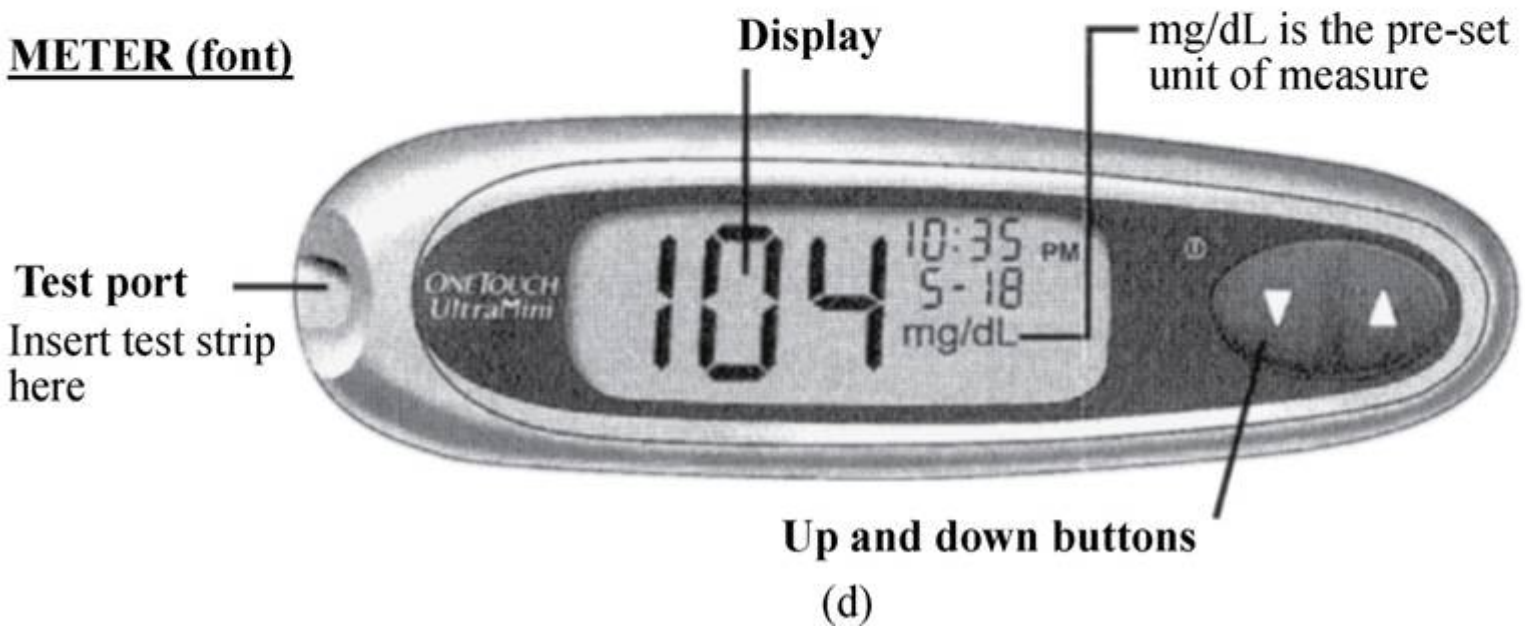
To provide weight reduction for the obese, how can we measure caloric intake and energy expenditure?

- Objective measurement of caloric intake is very difficult.
- The best I have seen is to measure chewing sounds. If you put your fingers in your ears and chew you will hear very clear chewing sounds through bone conduction.
- A miniature microphone can be placed in one ear to record chewing sounds in a behind-the-ear memory only when sounds occur.
- Spectral analysis can distinguish different foods to provide a very rough measurement of when you eat, how long you eat, and caloric input.

For diabetics, can we develop an implantable glucose sensor to provide a closed-loop control system for injection from an implantable reservoir?





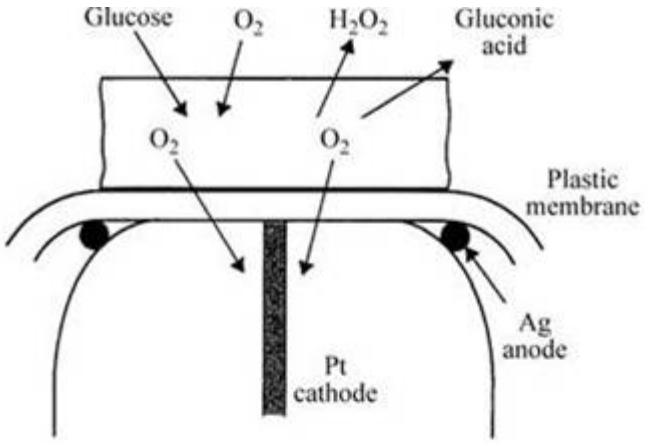


Present glucose sensor (a) A test strip is inserted into the meter. (b) A lance is released to lance the skin less than 1 mm. (c) The 1 µL blood sample is applied to the end of the test strip and drawn into it by capillary action. (d) 5 s later the meter displays the blood glucose in mg/dL. From www.LifeScan.com.

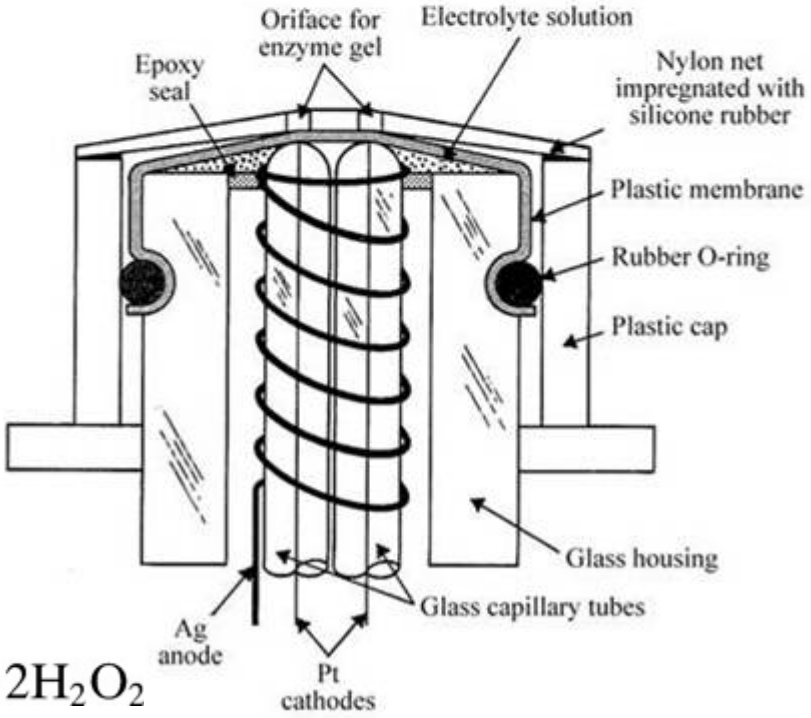
To build an artificial pancreas, we need an implantable glucose sensor.

(a) In the enzyme electrode, when glucose is present it combines with O2, so less O2 arrives at the cathode. (b) In the dual-cathode enzyme electrode, one electrode senses only O2 and the difference signal measures glucose independent of O2 fluctuations.

This sensor works in solution. But when implanted in the body, scar tissue forms around it so it lasts only a month. We need a biocompatible surface the body does not recognize.



(a)



(b)

$$\text{Glucose} + 2H_2O + O_2 \xrightarrow{\text{glucose oxidase}} \text{Gluconic Acid} + 2H_2O_2$$

Emphasis up to now has been on crisis medicine. You get some disease, and the physician treats it with drugs or surgery.

I suggest we could greatly reduce disease and increase longevity by focusing on prevention.

Men's expected age at death increases with no meat, exercise, nuts, low body mass index, and not smoking with a difference up to 10.6 years.