Chapter 2: Unit and Measurement

Quantitative description of organism is necessary to comprehend organism for analysis in engineering. A unit is necessary to describe the physical quantity. Ingenuity is necessary to measure biological phenomena quantitatively [3-5]. In this chapter, you learn the basics of the unit and the measurement.

2.1 Unit and Significant Figures

2.1.1 Unit

The parameter and the method to measure the **parameter** are necessary to describe biological phenomena quantitatively.

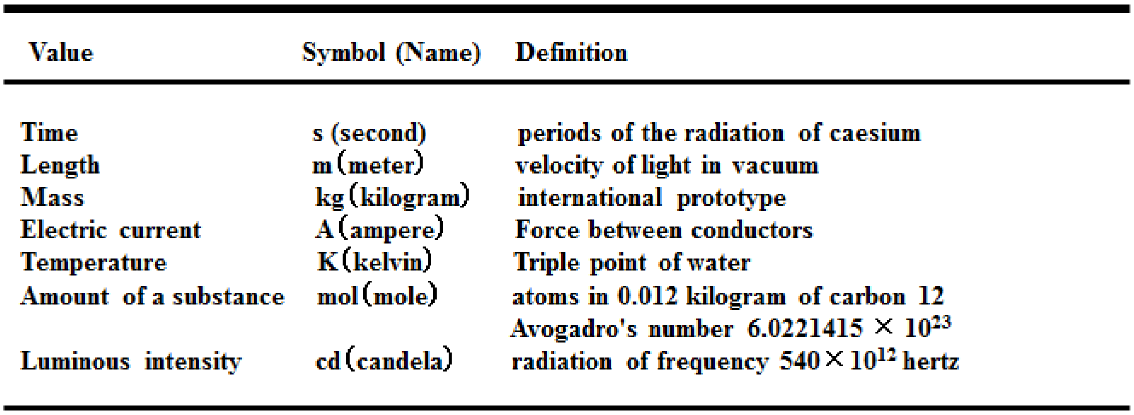
Primitive **unit**s are related to human body: a hand, a finger, and a foot. One second is approximately equal to the **cardiac cycle**. 100 in Fahrenheit is close to the body temperature. The relationship between the Celsius (C) and Fahrenheit (F) is represented by the equation 2.1.

$$F = (9/5)C + 32 \tag{2.1}$$

The variables should have the same units, when you calculate the sum or the difference between variables. Do not subtract kg from m. It is inconsistent with the concept of the unit system, if you use a value obtained by subtracting the weight from the height to represent a physique. On the other hand, the unit of the new variables defined by the multiplication or division of variables can be determined by the multiplication or the division of the units. For example, the unit of speed is defined by m/s.

SI unit system (**Le Systeme international d'unites**) is used for a universal system of units. The seven **base units** are defined: s for the time, m for the length, kg for the mass, A for the electric current, K for the temperature, mol for the amount of a substance, cd for the luminous intensity (**Table 2.1**). Each unit has been defined, while pursuing accuracy and reproducibility. The force of magnetic fields is studied as a new reference to the mass, although the prototype of kg (a cylinder consisting of platinum and iridium) have been used.

Table 2.1: SI base unit.



Value	Symbol (Name)	Definition
Time	s (second)	periods of the radiation of caesium
Length	m (meter)	velocity of light in vacuum
Mass	kg (kilogram)	international prototype
Electric current	A (ampere)	Force between conductors
Temperature	K (kelvin)	Triple point of water
Amount of a substance	mol (mole)	atoms in 0.012 kilogram of carbon 12 Avogadro's number 6.0221415 × 10^{23}
Luminous intensity	cd (candela)	radiation of frequency 540 × 10^{12} hertz

A unit assembled by the multiplication and division of the basic unit is called "**assembled unit**" [3]. Some of the assembled units have the unique name derived from the person's name: Newton [N] = [m kg s^{-2}], Pascal [Pa] = [m^{-1} kg s^{-2}], Joule [J] = [m^2 kg s^{-2}], Watts [W] = [m^2 kg s^{-3}], and others. An aggregate of the exponents of basic units is called "**dimension**". For example, the dimension of the density is a product of "mass" and "the minus third power of length". The dimensionless quantity has no unit.

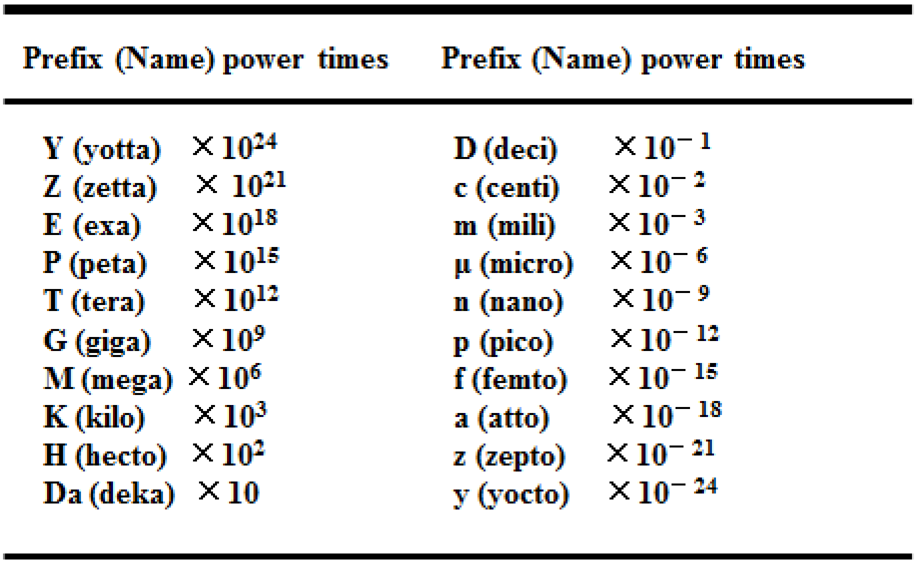
"Frequency" is the number of times per second. Although SI unit is s^{-1}, the specific unit of Hz (Hertz) is also available.

"Radioactivity" is expressed in dose per unit time. Although the unit is s^{-1}, the specific unit of Bq (becquerel) is also available.

The absorbed amount of the radiation is represented as "energy absorbed per mass of the body". Although the unit is J kg^{-1}, the specific unit of Gy (gray) is also available. The unique unit of Sv (Sievert) is used for the effects of the absorbed amount of the radiation on a living body. Although the unit of Sv is also J kg^{-1}, the value is multiplied by "quality factor". The factor depends on the type of radiation to evaluate the effect of radiation to the living body.

To express a large value or a small value, the prefixes are used to represent the power times of ten: Y, Z, E, P, T, G, M, k, h, da, d, c, m, μ, n, p, f, a, z, y (**Table 2.2**). In time, on the other hand, one minute for 60 seconds, or one hour for 60 minutes are used, rather than ks (kilo seconds), or Ms (Mega seconds).

Table 2.2: Powers of ten and unit prefixes.



Prefix (Name)	power times	Prefix (Name)	power times
Y (yotta)	$\times 10^{24}$	D (deci)	$\times 10^{-1}$
Z (zetta)	$\times 10^{21}$	c (centi)	$\times 10^{-2}$
E (exa)	$\times 10^{18}$	m (mili)	$\times 10^{-3}$
P (peta)	$\times 10^{15}$	μ (micro)	$\times 10^{-6}$
T (tera)	$\times 10^{12}$	n (nano)	$\times 10^{-9}$
G (giga)	$\times 10^{9}$	p (pico)	$\times 10^{-12}$
M (mega)	$\times 10^{6}$	f (femto)	$\times 10^{-15}$
K (kilo)	$\times 10^{3}$	a (atto)	$\times 10^{-18}$
H (hecto)	$\times 10^{2}$	z (zepto)	$\times 10^{-21}$
Da (deka)	$\times 10$	y (yocto)	$\times 10^{-24}$

Around the living body, the conventional units other than SI unit are often used. For example, mmHg is often used for the blood pressure. The unit of the pressure is Pa in SI unit. 1 mmHg is equal to 133 Pa.

For the quantity of heat in human, cal (calorie) or kcal (kilocalorie) is used. Originally, 1 cal was defined as the amount of heat required to raise 1 degree of the temperature for 1 g of water at the standard atmospheric pressure. Since the amount of heat depends on the temperature of the water, it is necessary to define the temperature of the starting point. In order to unify the variation due to the temperature, 1 cal is defined to be equal to 4.184 J.

For the concentration of the aqueous solution, g dl^{-1} is sometimes displayed as %, because the density is close to 1 g cm^{-3} = 100 g dl^{-1}. Do not confuse the percentage with SI unit. The unit of density in SI unit is kg m^{-3}. The unit is indispensable for the physical quantity.

2.1.2 Significant Figures

A measured value includes errors depending on the accuracy. In consideration of the error, the probable value is called “**significant figures**”. The leading number of zero at decimal fraction is not included in the significant digits. The number of zero at smallest digit is included in the significant digits, which contains the error.

For example, 0.0304 has three significant digits: 3, 0, and 4, except for the zero on the leading side. The number of 3600 has four significant digits: 3, 6, 0 and 0.

Because the error propagates in the calculation, it is necessary to pay attention to the significant digits. In the calculation of addition and subtraction, the error propagates at the position according to the decimal point. In the calculation of multiplication and division, the error propagates according to the significant digits (see Q 2.3).

The **cancellation of significant digits** may occur in the subtraction. For example, in the calculation of $3.14 - 3.13 = 0.01$, 0.01 has only one significant digit, although 3.14 has three significant digits.

50 years are 1.5×10^9 s = 60 seconds × 60 minutes × 24 hours × 365 days × 50 years. Six hours are 2.2×10^4 seconds = 60 seconds × 60 minutes × 6 hours. Thus, 6 hours are 1.4×10^{-5} times of 50 years, and the fifth significant digits of 50 years. The **brain death** is judged again after six hours. Six hours might not too long, compared with life time of human. If you measure the height of 1.70 m, the number has three significant digits.

2.2 Measurement

2.2.1 Resolution

The minimum value to distinguish two closest points is called “**resolution**”. Since each value changes at every moment in the living body, the value should be measured at the right time. The fast phenomena of variation should be measured within a sufficiently short interval (time resolution; cf. spatial resolution). On the other hand, the phenomenon to be evaluated by the average in the time should be measured over the sufficiently long period.

The potential fluctuation of the body surface due to the pulse propagation of the cell membrane potential at the heart (see 5.3.2) is called an “**Electrocardiogram**”. The electrocardiogram is measured as a potential difference between two points in the body. The different timing of the depolarization and repolarization between Va and Vb is measured as a waveform of $Va - Vb$ (**Fig. 2.1**).

If the action potential varies at the same time at every point, the potential between two points is zero. However, the timing of the depolarization and re-polarization are different at each point, so that the potential difference between two points is not zero. The counter direction of propagation of the electrical pulse of the action potential causes the reversal electrocardiogram (from plus to minus, or vice versa).

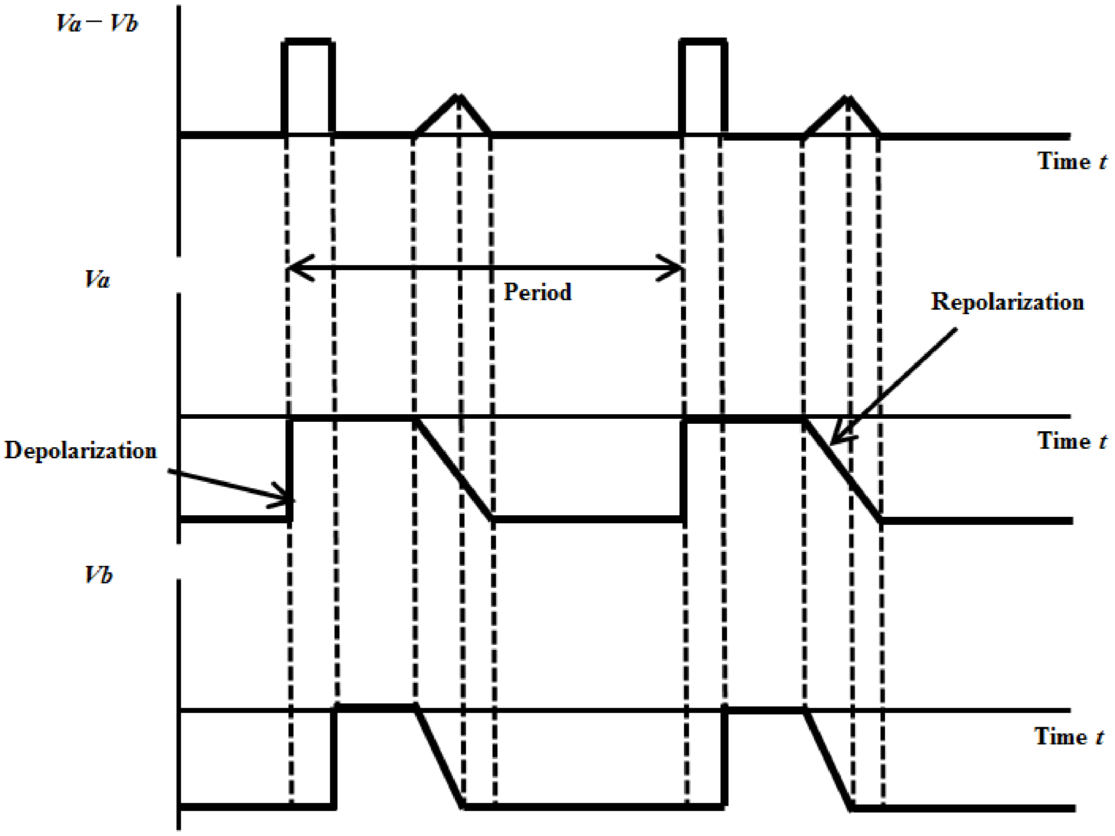


Fig. 2.1: Principle of electrocardiograph.

The propagation situation of potential pulses in the heart is estimated by fluctuation cycle, timing, and change direction of the electrocardiogram. The waveforms can be classified by spectral analysis [6]. It helps the diagnosis of heart disease as a screening test.

There are events that cannot be determined in the instantaneous measurement. In the **determination of brain death**, the electroencephalogram is measured again after 6 hours. The **Holter monitor** records the electrocardiogram over 24 hours. It is useful to detect arrhythmia, or the function of the pacemaker.

In the non-uniform and non-equilibrium subject, it is necessary to decide the range of measurement: local or wide (spatial resolution). In the **immunostaining**, the distribution of the targeted protein in tissues and cells is measured by applying the antigen-antibody reaction (**Fig. 2.2**).

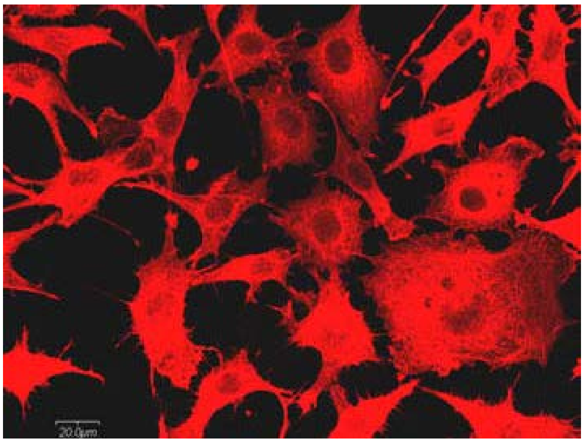


Fig. 2.2: Immuno-staining. Dimension is 0.25 mm from left to right.

2.2.2 Measurement System

Not only the measured object, but also the situation of the entire system including the measuring device should be controlled in the measurement. For example, it is necessary to consider the frequency characteristic of the electric circuit of the measuring device, when the measuring system including an electric circuit in the measuring device side.

The four-terminal method (**four-terminal method**) is applied in the measurement of the electrical resistance, when the resistance of the electrode of the measurement device is not small enough compared with that of the specimen. In the method, the terminals are divided into two kinds of terminals: the “current terminals” and “voltage terminal”. The higher current flows through the current terminal. The lower current flows, on the other hand, through the voltage terminal. The effect of the drop in voltage at the voltage terminal is minimized by reducing the current.

The number of electrodes inserted to the specimen is reduced to one in the **vibrating electrode technique** (**Fig. 2.3** (a)). In the method, the resistance between the fixed electrode and the vibrating electrode varies between R and R + ΔR. This ΔR reflects the information of the resistance at vicinity of vibrating electrode.

The local electric resistance at vicinity of the electrode is measured by picking up the signal corresponding to the frequency [7]. For example, by replacing the position of the fixed electrode and the vibrating electrode between the egg yolk and the egg white, the different signal can be detected. The difference of the signal depends on the difference between the electric resistance of the egg yolk and the electric resistance of the egg white (see 4.1.2). The thin electrode tip can be inserted into the small biological cell (**Fig. 2.3(b)**).

The human himself can be studied in comparison with the measurement system: the sensory organ as a sensor, the nervous system as a signal transmission device, and the brain as a signal processing and a **memory** (**Fig. 2.4**).

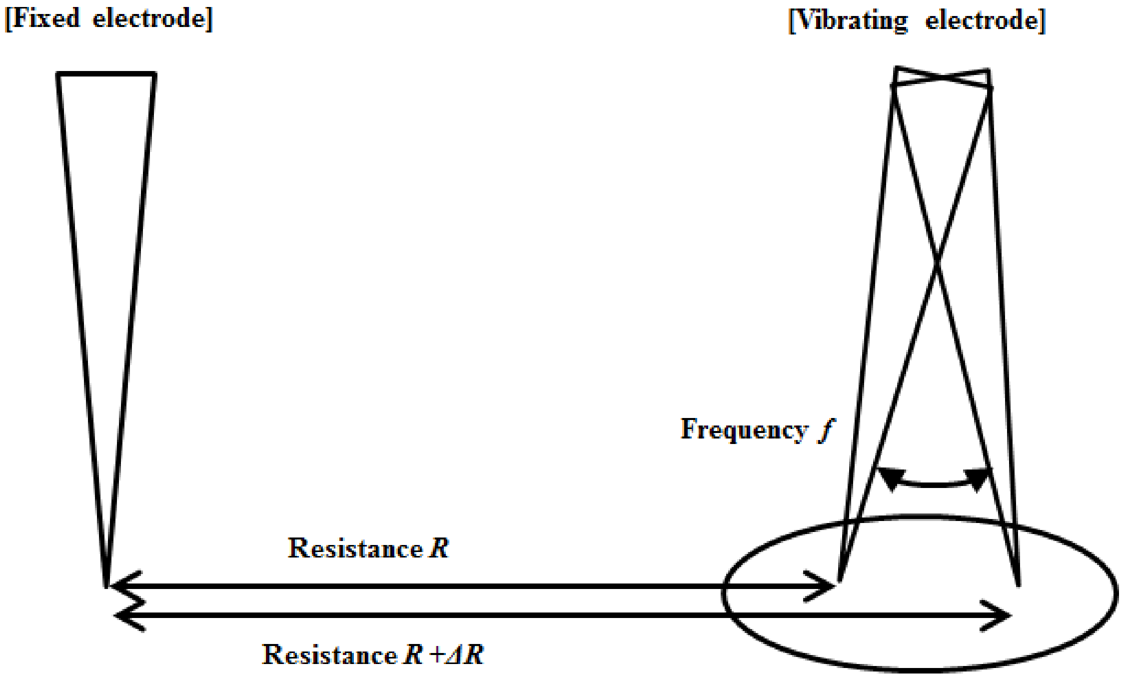


Fig. 2.3(a): Vibrating electrode (principle).

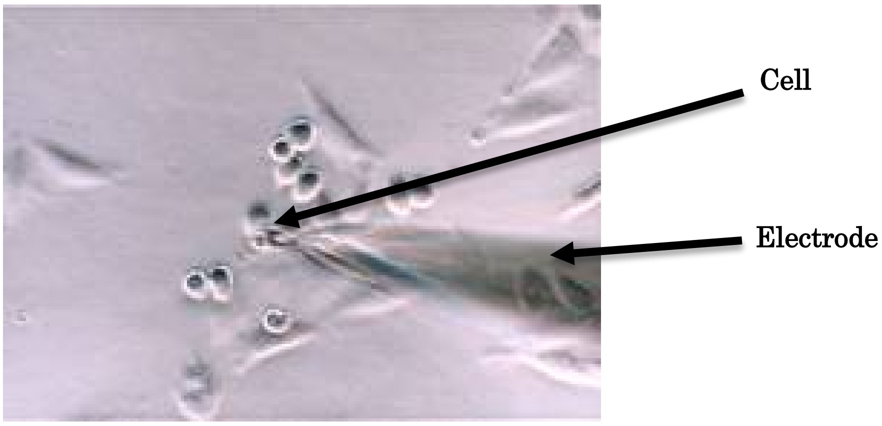


Fig. 2.3(b): Vibrating electrode. Dimension is 0.25 mm from left to right.

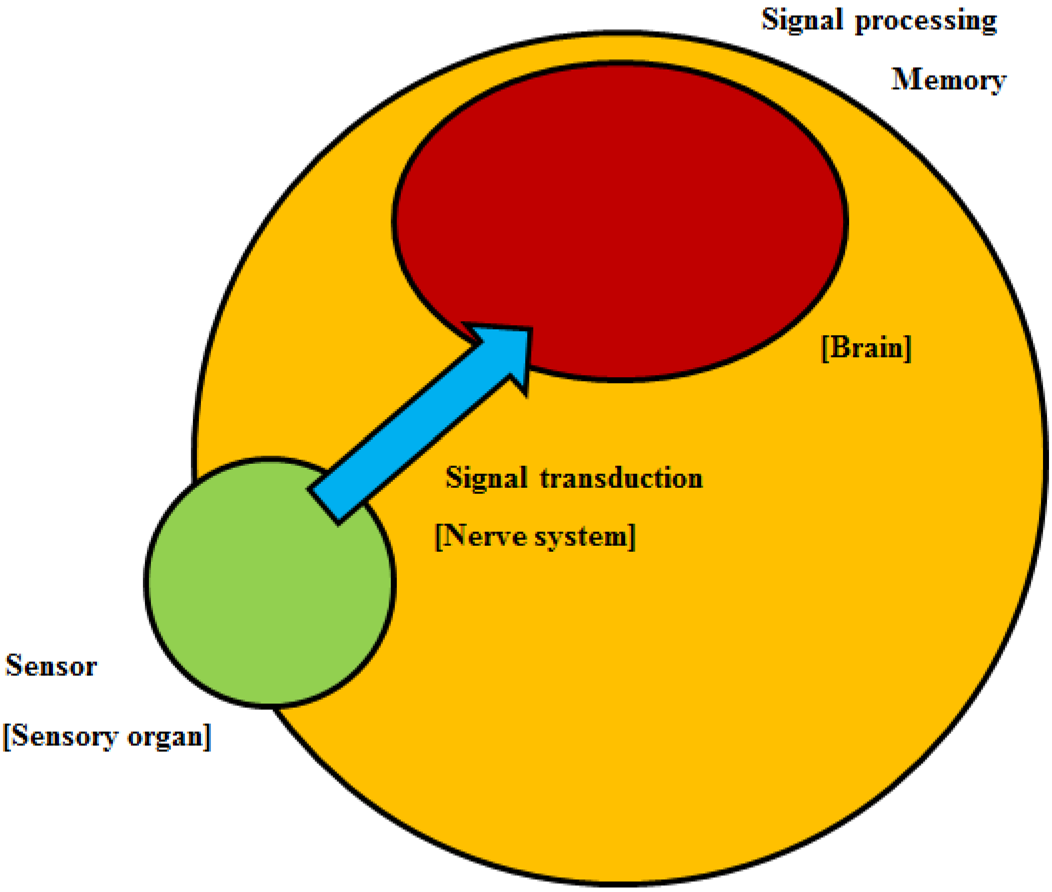


Fig. 2.4: Biological system.

2.2.3 Alternating Component

The **cell membrane** consists of **lipid bilayer**. Both the adipose tissue and the cell membrane have a large electrical resistance to direct current (**Fig. 2.5**). They are similar to the capacitor in the electric circuit.

At the capacitor, the fluctuation of the voltage generates the movement of the charge, but the timing of the peak of the voltage shifts from that of the current. When the charge transfer speed (the current) becomes zero after the peak value, the accumulation of the electric charge saturates. At that time, the voltage reaches to the peak value. Through the cell membrane, the high frequency signal is more selectively transmitted than the low frequency signal.

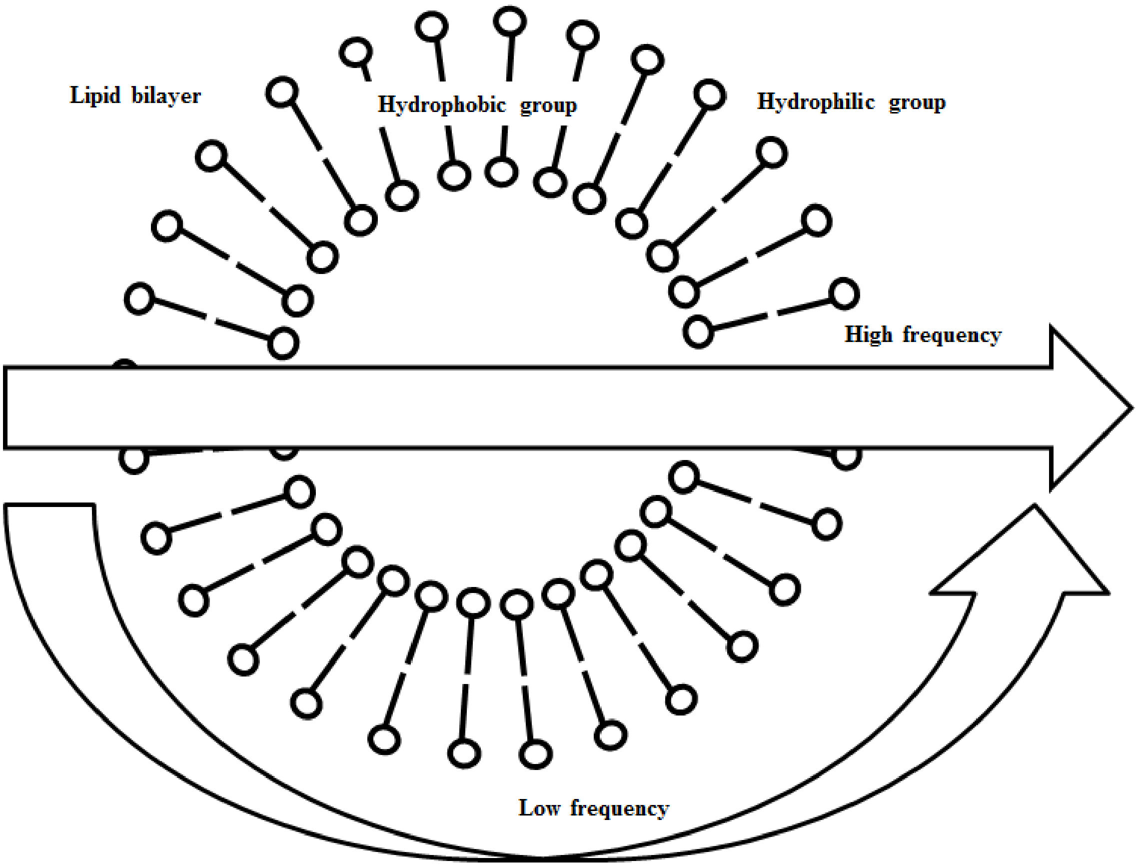


Fig. 2.5: Electric current through lipid bilayer.

The combined signal periodically displays the figure of ellipse in the *xy*-plane, when the sinusoidal signals are simultaneously displayed at *x*-axis and at *y*-axis: the sine wave of the alternating current *i* is displayed at *x*-axis, and the sine wave of the alternating voltage *v* is displayed at the *y*-axis, respectively. The locus of points drawn by two **simple harmonic vibrations**, which is orthogonal each other, is called **Lissajous figure**. In **Fig. 2.6**, *t* is time, *T* is the period, and the arrow indicates the rotational direction of the tracings.

The ratio of the capacitance component reflects the distribution of cell membranes and fat tissue. The ratio of the capacitance component of the tissue impedance detected by the Lissajous figure can categorize the type of tissue: according to the density of cells, arrangement of cells, and the fat components (**Fig. 2.7**) [8].

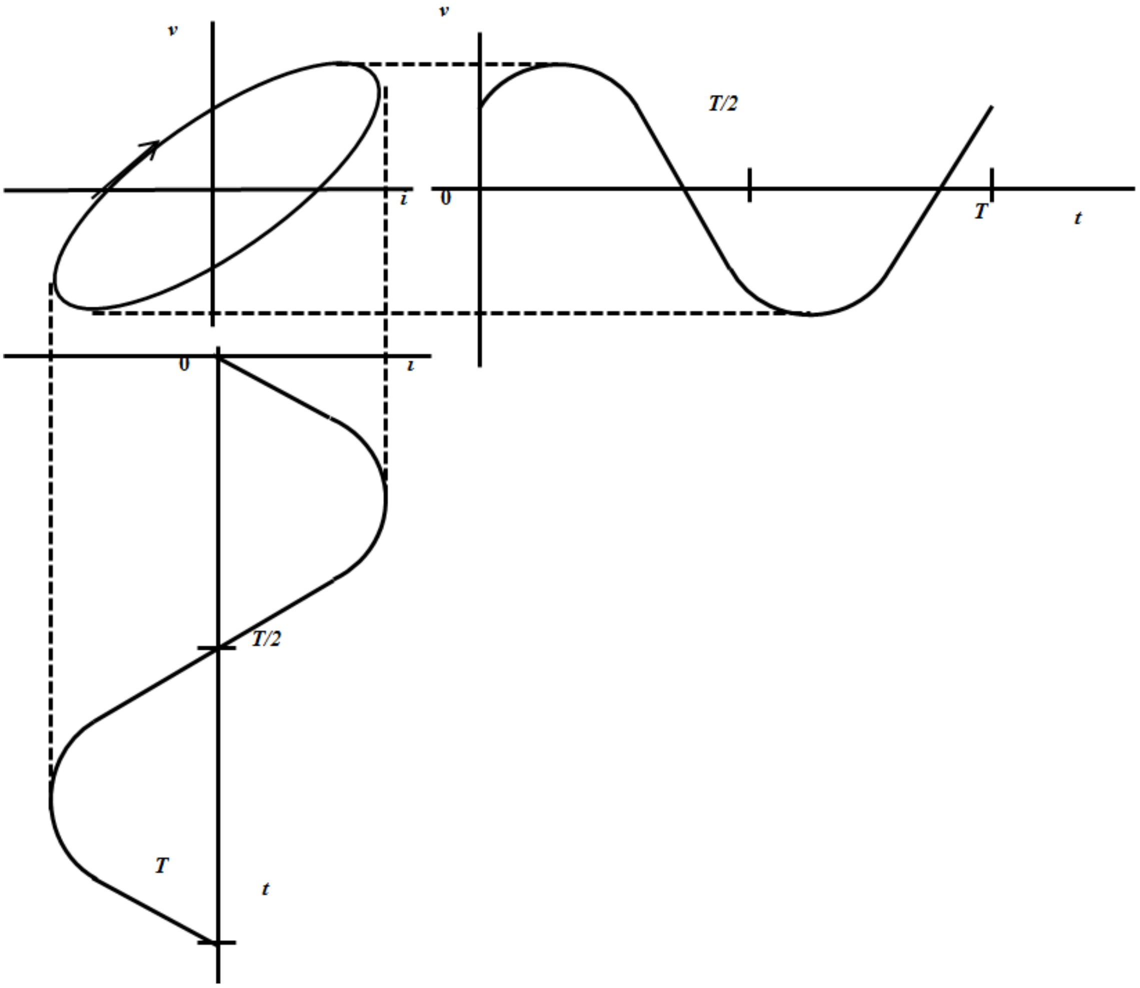
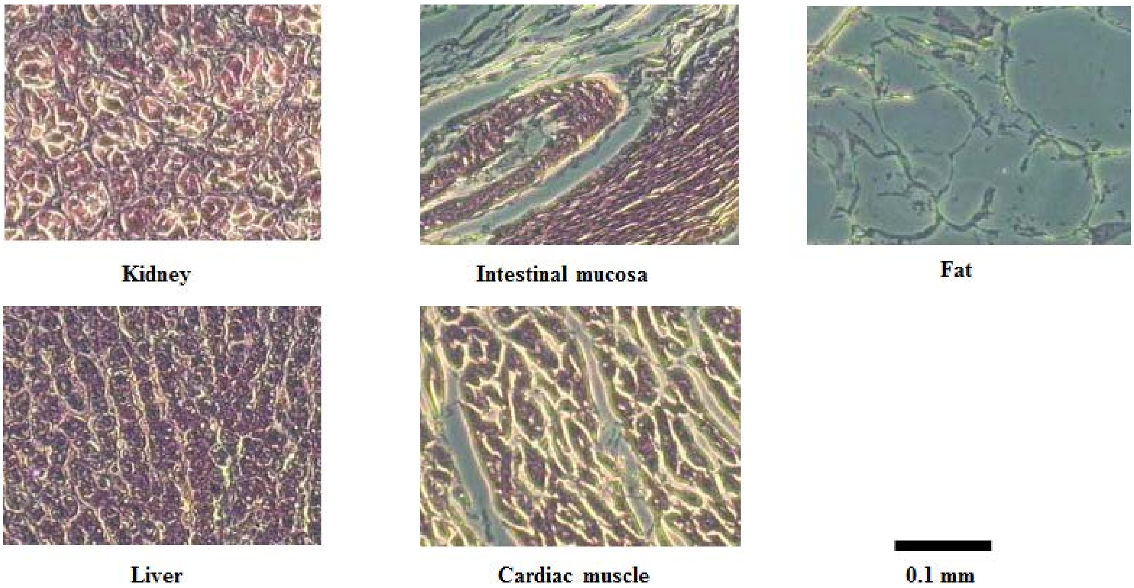


Fig. 2.6: Lissajous figure.


Kidney

Intestinal mucosa

Fat

Liver

Cardiac muscle

Fig. 2.7: Tissue grouping.

2.2.4 Non-invasive

In the physiological liquid, pH (see 5.1.2) is an important environmental conditions for the physiological activity. It is usually measured by a pH electrode immersed in the solution. The transmittance of light, on the other hand, would help for local measurement without immersing the electrode (**Fig. 2.8**). When the pH indicator is dissolved in the culture solution, the transmittance of light of a specific wavelength of the indicator is available [9].

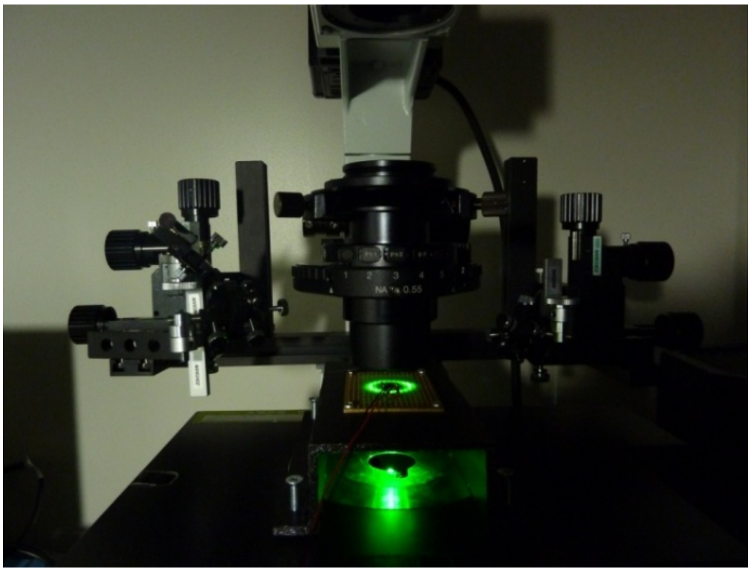


Fig. 2.8: pH measurement with light.

Laser light has an uniform wavelength, and has the straight advancing property (**Fig. 2.9**). It has advantage for non-contact measurement and local measurement. The light from the light source is led to the target, through a filter or a prism. It can be applied to the measurement of the pulsatile deformation of the arterial vessel wall [10], and of shrinkage of the cultured myotube [11].

The process of the measurement might change the state of the object to be measured. To prevent the artifact of the contact, the non-contact measurement is effective. The artifact on the living body is called **invasive**. The **non-invasive measurement** is the ideal.

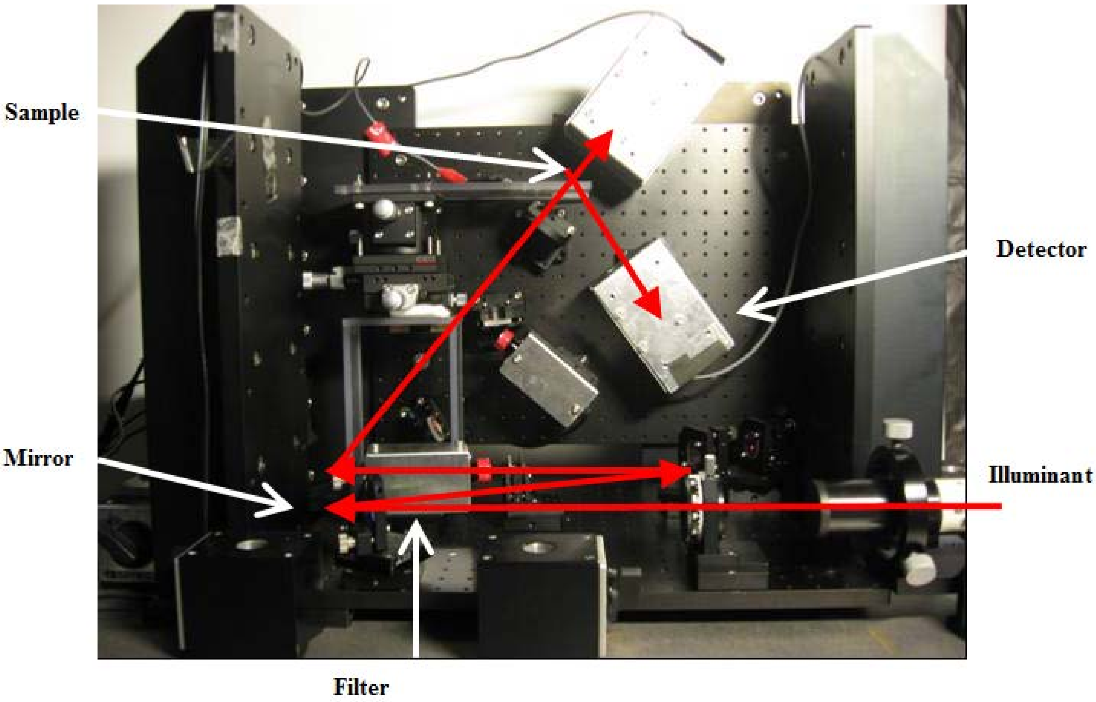


Fig. 2.9: Measurement with laser.

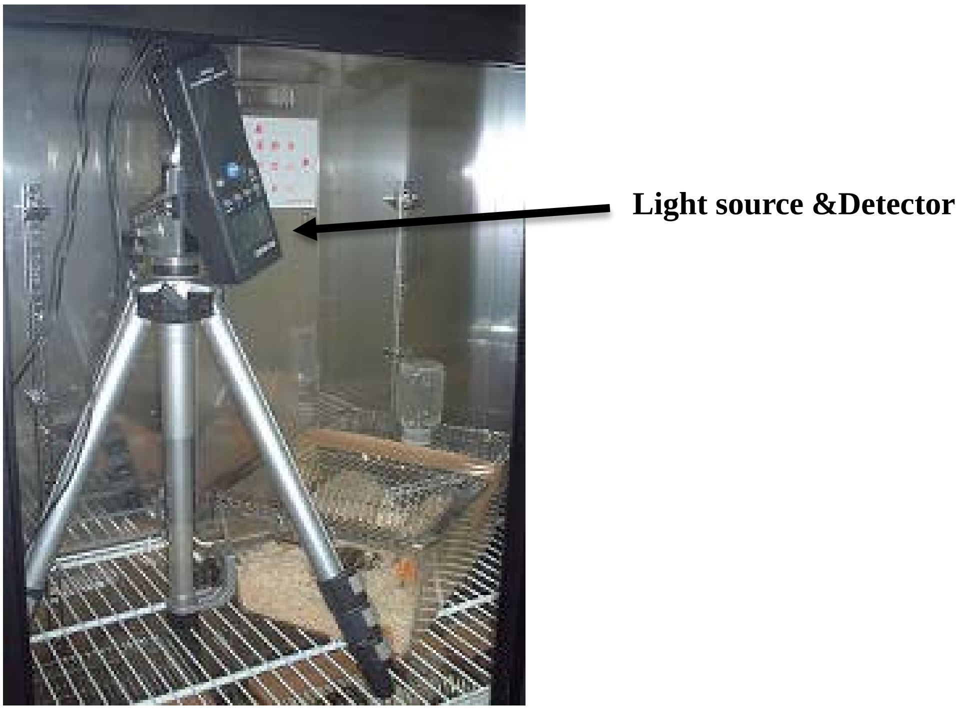


Fig. 2.10: Measurement of skin temperature with infra-red ray.

The probe of the conventional thermometer contacts with the measurement point. The infrared thermometer, on the other hand, can measure the temperature at the skin of a hibernating animal without contact (**Fig. 2.10**) [12].

The pressure difference at both ends of the inserted flow resistance is often used to measure the flow rate (see 4.2.1). The movement of the float is used for the measurement of the flow rate. These devices inserted into the flow path, however, disturb the original stream.

The "**Doppler effect**" at the reflected wave from the floating particles is available to measure the flow speed of the fluid. The method does not mechanically disturbe the original stream. "The wave propagation speed" also depends on the flow speed of the fluid. Doppler effect at the reflected wave from an erythrocyte in the blood flow is also available to measure the flow rate of blood.

The **electromagnetic flowmeter** can be applied to measure the flow of the physiological liquid, because the physiological liquid includes electrolytes. When the constant magnetic field is perpendicularly applied to the electric current, a voltage is generated in a direction perpendicular to both. The voltage value is proportional to the current. The increase in the flow rate of the physiological fluid has the same effect as the increase of the current, the flow rate is measured by the voltage (**Fig. 2.11**).

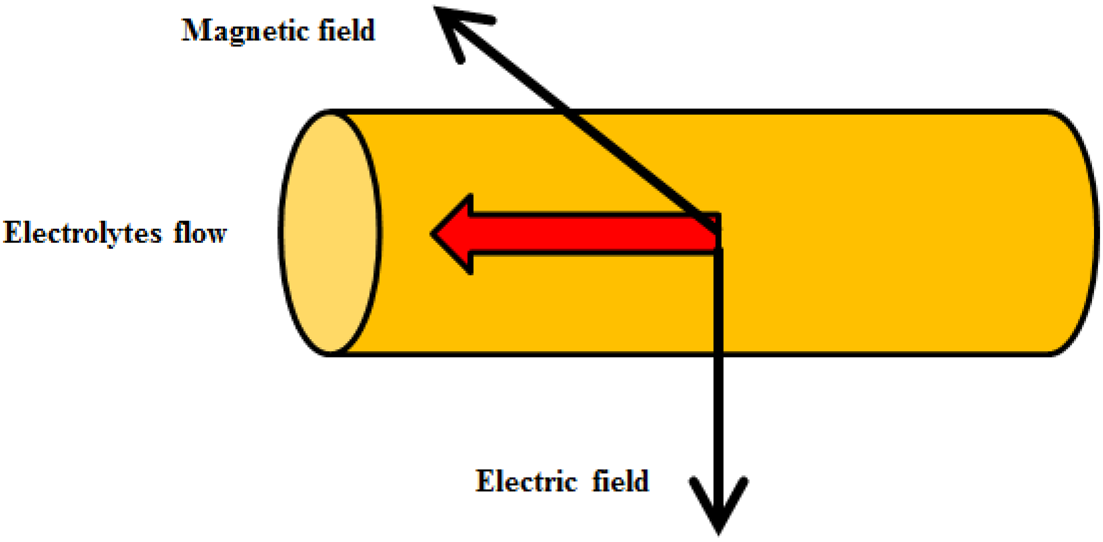


Fig. 2.11: Principle of electromagnetic flowmeter.

2.2.5 Non-linear and equilibrium

When the output is proportional to the input, a linear relationship is available. Non-proportional relation, on the other hand, is called **non-linear**. In the living body, the first signal does not often appear below the **threshold**. The variable region of the measurement should be carefully selected in the non-linear system.

In the measurement dependent on the environment, the accuracy of measurement can be improved by comparison with a standard signal placed in the same environment. The balance with the standard signal is called “**zero method**”.

For example, by equilibrium with a standard weight in the balance, the mass can be measured independent of gravity change (**Fig. 2.12**): on the moon, or on the earth. When the current *i* does not flow through the galvanometer G at the “**Wheatstone bridge**” (**Fig. 2.13**), the potential at point b is equal to that at point c. In this case, Eq. 2.2 is established among the resistors R_1, R_2, R_3, and R_x.

$$R_2 / R_1 = R_3 / R_x \tag{2.2}$$

When the three resistances R_1, R_2, R_3 are known, the unknown resistance R_x is calculated.

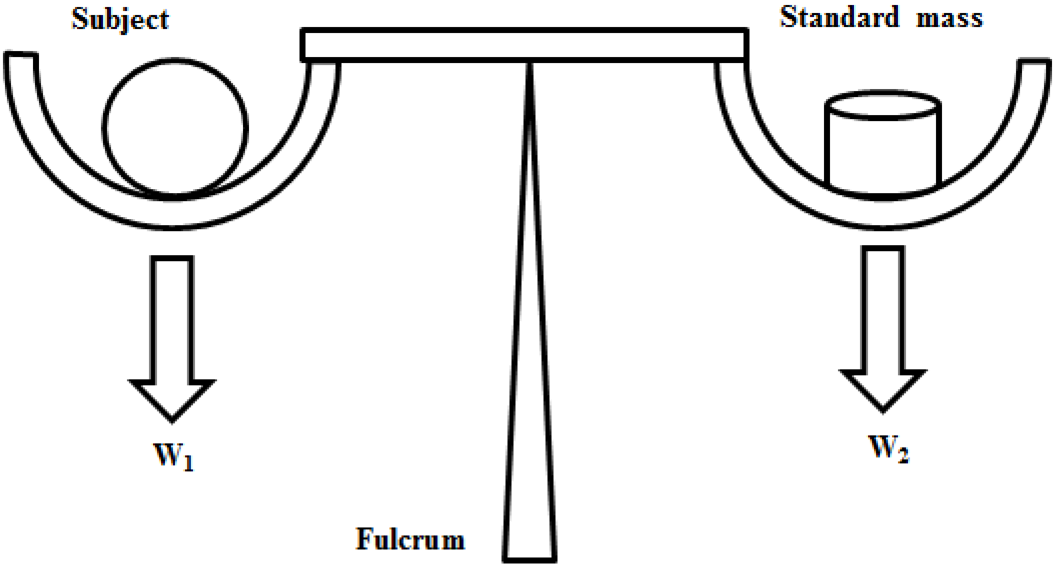


Fig. 2.12: Gravitational equilibrium.

2.2.6 Noise and Statistics

The received signal often includes the various signals. The extra signal is referred to **noise**. The ratio between the targeted signal and the extra signal is called SN ratio (**signal to noise ratio**).

Using an appropriate **probe**, the targeted signal can be emphasized by the principle of resonance. For example, the secondary coil inserted in the cylindrical cage of the primary coil (**Fig. 2.14**(a)) is effective to improve the quality of the **magnetic resonance image** of the cartilage of the knee joint (Fig. 2.14(b)) [13]. The fitting of the secondary coil to the knee improves capturing the signals from the knee by the high SN ratio.

A living body has **individual difference**. The state of the living body changes every time, including the growth. The variation of the measured value should be considered in the bio-measurement.

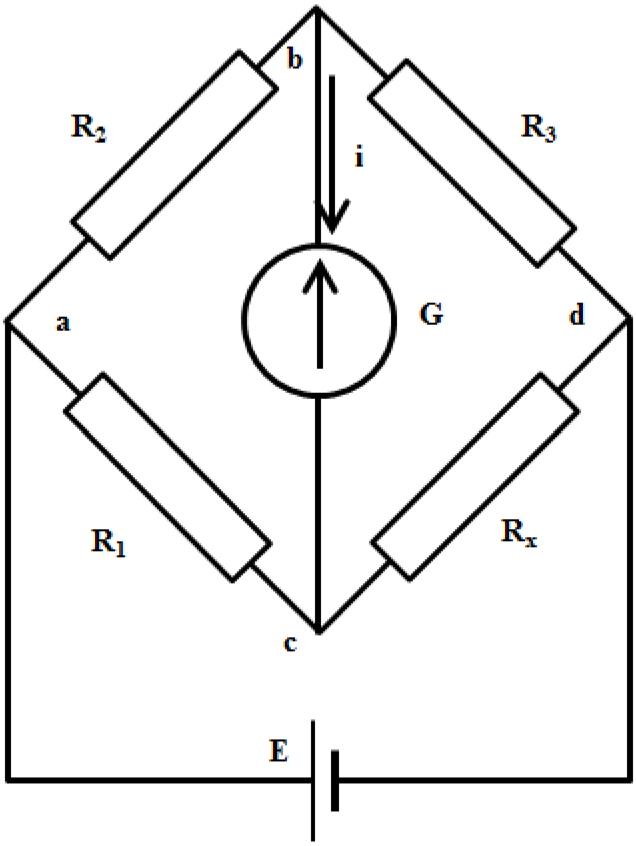
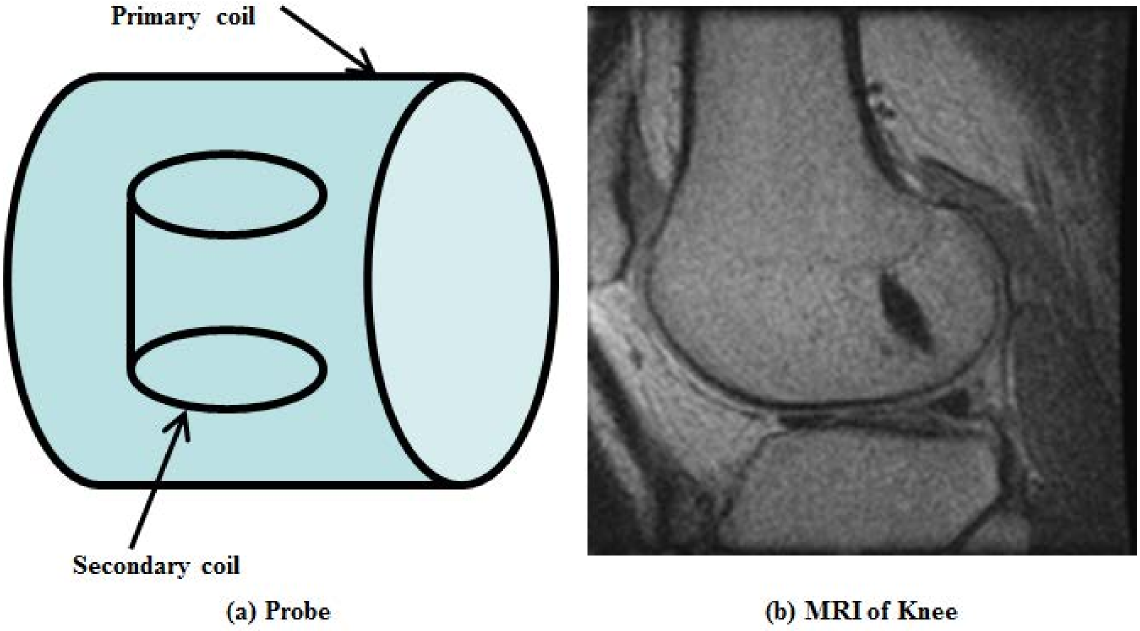


Fig. 2.13: Wheatstone bridge.



(a) Probe

(b) MRI of Knee

Fig. 2.14: MRI (magnetic resonance image).

In order to correct the errors due to scattering, μ is used as the **mean value** of the values x_k measured N times (from k=1 to k=N).

$$\mu = \frac{1}{N}\sum_{k=1}^{N}(X_k) \qquad (2.3)$$

The **standard deviation** σ is used for the index of fluctuation.

$$\sigma = \sqrt{\frac{\sum_{k=1}^{N}(X_k-\mu)^2}{N}} \qquad (2.4)$$

The **statistical test of the difference between the mean values** is one of the statistical techniques to determine the effect of the specified condition applied on the living body. The significance is statistically tested on the difference between the mean values of two groups: the condition applied group, and the control group.

The number of data to determine the statistical trend is called **number of samples**. The **normal distribution** is often applied to statistical calculations. The distribution pattern of data should be examined before statistical calculations. The sufficient numbers of samples are necessary for the statistical analysis.

Two groups (A and B) are described in the following example. Each group has the same number of samples N, and the same standard deviation σ at the normal distributions. The mean value of each group is μ_A or μ_B. The difference between the average values ($\mu_A - \mu_B$) is equal to σ. In this case, it is estimated that there is a difference between the mean values between the group A and group B with the **significance level** of 5% at the number of samples of 9, and of 1% at the number of samples of 16 (**Fig. 2.15**). The smaller significance level shows the smaller error in the estimation for the whole data.

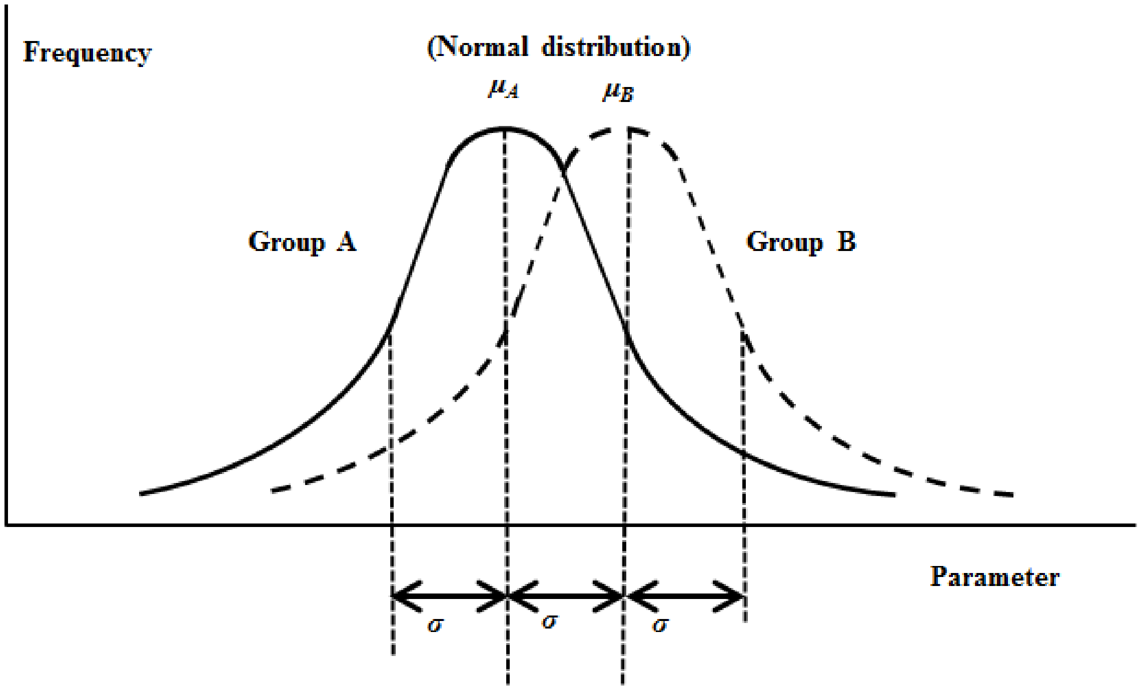


Fig. 2.15: Test of difference in the mean value.

Questions

Q 2.1: Display each value with the product of base unit of SI. Arterial pressure of 100 mmHg, cardiac output of 6.0 liters per minute, pulse rate of 70 times per minute, one day metabolism of 1000 kcal, heart power of 1.0 W.

Q 2.2: Explain that 1 + 1 + 1 is not always equal to 3 in measurements.

Q 2.3: Confirm the significant digits of the calculation result of 3.14 × 2.236. Consider each value as a result of rounding in the lower position.

Q 2.4: List the example of “zero method” with explanation.