BASIC INSTRUMENTATION SYSTEMS

1.1 INTRODUCTION

The term "instrumentation" has a multitude of different meanings to scientists in various fields of endeavor. To the physician, instruments are the tools of his trade; therefore, anything from an ear speculum, which is placed in the external ear to help visualize the eardrum, to a surgical retractor, which holds back the edges of an incision, is considered to be an instrument. The engineer is more specific in his or her use of the term "instrumentation". We refer to instrumentation as those pieces of equipment that may be used to supply information concerning some physical quantity (usually referred to as a variable). This variable may be fixed and thus have the same value for a long time for a given physiological system, or it may be a quantity, that can change with time.

In considering biomedical instrumentation, we will, out of necessity, have to limit ourselves to instruments that fit the engineering definition. We will be concerned with those instruments that directly obtain physiologic information from organisms. While the examples of the ear speculum and the surgical retractor can be considered instruments because they make it possible for the physician to visually observe parts of the body that could not be normally seen, we will not consider these, since indeed the observation is made by the physician rather than by the devices described. On the other hand, we do not want our definition of instrumentation to be too limiting, for indeed when fiber optic image conduits for visualization within the body are considered, we will certainly want to classify them as biomedical instruments, although their function is only a small extension of that of the speculum or retractor described above.

Instruments, therefore, are used to provide information about physiologic systems. In providing such information the instrument is carrying out an *indicating function.* This function may be achieved by a moving pointer on a meter, an aural or visual alarm, or by flashing numbers or words on a screen to describe the variable being measured. Many instruments not only indicate the value of a variable at a particular instant in time, but can also make a permanent record of this quality as time progresses, thus carrying out a *recording function* as well as an indicating function. Instruments that present the measured variable on a graphic chart, a computer screen, a magnetic or compact disk, or a printed page carry out the recording function. Today computers perform these functions by storing data in digital form on media such as semiconductor memory and magnetic or optical discs.

A third function that some instruments perform is that of *control.* Controlling instruments can, after indicating a particular variable, exert an influence upon the source of the variable to cause it to change. A simple example of a controlling instrument is an ordinary room thermostat. If the room is too cold, the thermostat measures the temperature and senses that it is too cold; then it sends a signal to the room heating system, encouraging it to supply more heat to the room to increase the temperature. If, on the other hand, the thermostat determines that the room is too hot, it turns off the source of heat, and in some cases supplies cooling to the room to bring the temperature back to the desired point. In our discussion of temperature control later on, we will look more closely at this controlling function of instruments, however, for the

most part, we will be concerned with instruments that only indicate and record.

In engineering we often find it necessary to carry out rather complex operations. These can be done by a group of connected component parts, each of which carries out a single relatively simple function. This connected group of components is known as *a system.* Therefore, in engineering we can take a group of simple, single-function blocks and put them together in such a way that we have a system that can perform operations far more complex than those of the individual blocks. This block concept will be very useful in the description of biomedical instrumentation systems. Often we find that a system can be graphically described by drawing a diagram of these blocks showing how they are connected together to achieve the desired function. Such a diagram is known as a block diagram, and it is a good way to show the interrelationship of the system components.

1.2 GENERAL INSTRUMENT SYSTEM

All instrumentation systems can be generally described by the block diagram of Figure 1.1. Here the system consists of three different parts: the *sensor,* the *processor* and the *display* and/or *storage.* Let us examine each block separately to determine its function in the overall system.

The *sensor* converts energy from one form to another, the second being related to the original energy in some predetermined way. As an example, let us consider a microphone. Sound energy in the air surrounding the microphone interacts with this sensor, and some of the energy is used to generate an electrical signal. This electrical signal is related to the sound entering the microphone in such a way that it can be used to produce a similar sound at a loud speaker when appropriately processed. Thus, the microphone has acted as a transducer. The loud speaker has also acted as a transducer since it converted the electrical energy back to sound. The terms *sensor* and *transducer* are often used interchangeably. We will distinguish them by considering a sensor as a very low energy device that performs an energy conversion for the purpose of making a measurement.

There are many other possibilities than the above example for energy conversion by a transducer. There are represented by the diagram in Figure 1.2. As we move around the periphery of the figure we find the various forms of energy that are encountered by the instrumentation specialist. *Mechanical energy* refers to the potential and kinetic energies of a mass of any material. Although *acoustic, hydraulic* and *thermal* energies would all fit into this classification, these other quantities are encountered sufficiently by instrumentation specialists that they are considered separately. Acoustic energy refers to the energy of sound waves, either in air or some other conducting medium such as biologic tissue. Hydraulic energy refers to the energy contained in a fluid (liquid or gas). This energy can be in the form of kinetic energy of a flowing fluid, or it can be the potential energy of a fluid under pressure. Thermal energy refers to the energy available in a material as a result of its temperature.

Figure 1.1. Block diagram of a general instrumentation system.
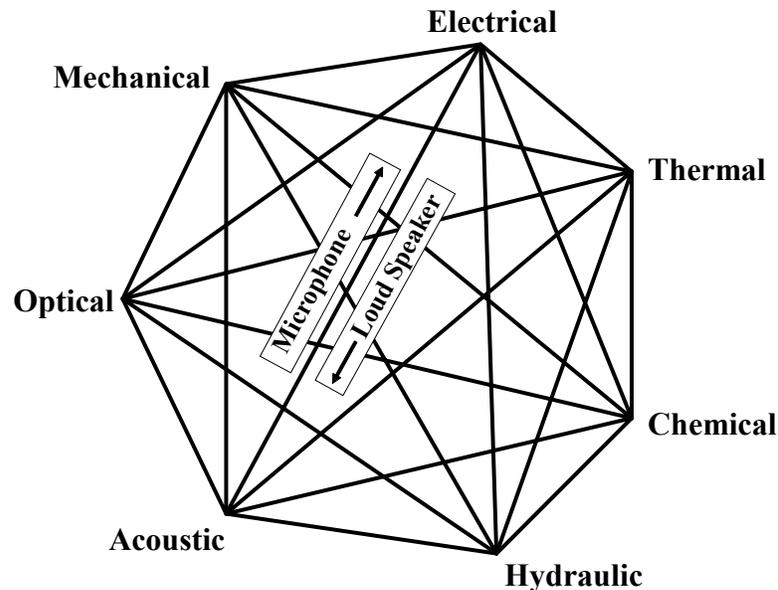
Possible Types of Transducers

Figure 1.2. Chart of different possible types of transducers.

Another form of energy that is of particular interest to the biomedical instrumentation specialist is *electrical energy*. This is the energy that can be imparted to an electric charge and is a useful means of conveying information in instrumentation systems. *Optical energy* refers to energy in the form of light or electromagnetic radiation very similar to light such as infrared and ultraviolet radiation. With the advent of the laser, this has become important in medical instrumentation systems. Finally, *chemical energy* refers to the energy associated with the formation and reaction of various chemical compounds.

It is theoretically possible for a transducer to convert some energy in any one of the forms mentioned above to any other of the forms. Therefore, we can represent the transducers by the lines drawn between the different energy forms on the diagram. For the microphone example described above, this transducer would be located on the line connecting acoustic and electrical energies. Since, in the microphone, acoustic energy is converted to electrical energy; we would represent this on the line with an arrow pointing from acoustic to electrical energy. If, on the other hand, we consider the loud speaker; here electrical energy is converted into sound waves. We would represent this transducer on the same line, but the arrow would point from electrical to acoustic energy.

There are many other examples of transducers that could be placed on this chart. Some of these transducers are *reversible; i.e.,* the arrow on the line could be drawn in either direction. An example of a reversible system might be the storage battery used in an automobile. When it is used to supply electrical energy to start your automobile, it is a chemical to electrical transducer and so the arrow would point towards electrical energy. However, when your car is running, electrical energy is supplied back to the battery to replace the charge depleted by starting the car. In this case, the battery is serving as an electrical to chemical transducer. Since the battery is the same in both cases, it is said to be *reversible* type of transducer.

There are some types of transducers that are not reversible. For example, consider a light bulb. This is an electrical to optical energy transducer, since when we supply an electric current, it lights up producing optical energy. However, with common light bulbs we cannot shine a light on it and expect to find any electrical energy produced at its terminals; therefore, this device cannot be used as an optical to electrical transducer. Thus, it is said to be an *irreversible* transducer.

Although there are many kinds of devices that convert one form of energy to another as illustrated in Figure 1.2, we usually only refer to those that are used for purposes of gathering information as sensors. Thus devices such as electric motors, electric heaters, steam boilers, etc. would not be considered as sensors although they carry out the same function but at much higher energy levels.

There are three general requirements for transducers used in instrumentation systems. These are:

1. Accuracy
2. Stability
3. Lack of interference with the physiological variable being measured.

It is obvious why an instrumentation sensor must be *accurate.* It is essential to know how the output signal from the sensor is related to the input quantity. In most applications it is desirable that this relationship be *linear,* however as we see below, this is not essential, and with today's ready access to computers and microprocessors, nonlinear characteristics can be "linearized" with little effort provided the non-linear characteristic is *reproducible.* This means that the output signal is directly proportional to the input quantity. In some cases, non-linear relationships are desirable. For example, let us consider the microphone used as a sensor in an instrument for measuring the intensity of sound in a room. Since the human ear responds to sound intensities logarithmically rather than linearly, in many applications it would be desirable for the sound intensity meter to operate in the same way. One way of achieving this would be to use a microphone that had a logarithmic relationship between the sound energy input and the electrical output. Another approach would be to use a linear microphone and a logarithmic amplifier to process the signal.

Although linearity of a sensor's calibration characteristic is often a desired feature, sensors with non-linear calibration characteristics are also very useful when computers are a part of the instrumentation system. It has always been possible to use the computer processing

of the sensor output signal to "linearize" a non-linear characteristic. There are also situations, as illustrated in the previous paragraph, when it may be desirable for a particular application to have a special functional relationship between the variable being sensed and an instrument's output, and a computer can make this possible as well. One of the roles of a computer in an instrument's processing block is to convert the sensor's actual calibration characteristic to the calibration characteristic that is desired for the instrument. The important feature of the sensor in this case is no longer linearity but stability and reproducibility as described in the next paragraph. As long as the sensor's calibration characteristic is known and does not change, processing by a computer can convert this to the characteristic that is desired.

A sensor must be *stable* if it is to be able to provide reproducible data time and time again. Changing of the sensor's properties with time, temperature, humidity, gravitational pull, etc. means that it cannot be used as the first stage of a reliable instrumentation system unless it is periodically used to measure known quantities considered to be *calibration standards* as a means of calibration.

Finally, the presence of the sensor must not disturb the system being measured in any way if it is to provide accurate data. In many measurements this cannot be achieved, and so the sensor is made to provide a minimum of disturbance to the system being measured. Since the sensor converts some of the energy of the variable being measured into a new form, it takes this energy away from the system being measured. If this is a substantial amount of energy, it can indeed result in an error in the measurement. For example, to measure the temperature of a body, we introduce a thermometer into the body and it is allowed to stay until its temperature is the same as that of the body. Thus, if we submerge a thermometer into a very small test tube of warm water, the thermal energy of the water is used to heat the thermometer. But we could also look at it this way: the cold thermometer is used to cool the warm water. If the thermometer is not very small compared to the amount of water present, this cooling effect cannot be neglected and will indeed change the temperature of the water. Thus this will give an erroneous reading as far as the original temperature of the water is concerned. It is, therefore, important to consider the effects of a given sensor on a measurement when selecting the sensor to make that particular measurement.

The electrical signal produced by most sensors is generally very small and must be modified to be useful in instrumentation systems. This modification of the sensor's signal is carried out by the second block in the instrumentation system (Figure 1.1), the processor. The *processor* operates on the sensor output signal to modify it to a form that can be used to suitably present or store data on the variable measured by the sensor. To do this, there are several different functions that can be performed by the processor. These are defined below and will be described in greater detail later on.

> 1. *Amplification* - the process of increasing the amplitude or strength of the sensor output signal without varying it in any other way.

> 2. *Modulation and Demodulation* - the process of imposing or removing a signal (the information) upon another signal (the carrier) that is used to convey the original information. Modulation puts the information on the carrier, and

demodulation recovers the original information from the carrier.

3. *Frequency Selection* - the process whereby a signal containing a group of different frequencies is filtered, allowing only certain desired frequencies to pass, while blocking all other frequencies.

4. *Transmission* - the process of taking a signal from one point in space and conveying it, undistorted, to another point.

5. *Wave Shaping* - the process of purposely distorting a signal to give it certain desired characteristics.

6. *Isolation* - the process of maintaining a signal so that it cannot be easily modified by interfering signals or random noise.

7. *Logic* - the processes whereby certain signals interact with one another according to preset rules that allow elementary decisions to be made.

8. *Conversion* - the process of transferring a signal from analog to digital format or vice-versa.

These definitions, by necessity of their simplicity, are extremely vague. It is only through specific application and examples of these processor types that we will get a good feeling as to their meaning. It is hoped that through the analysis of the examples that follow, a working understanding of these terms will be obtained.

Similar to the sensor, the processor has several requirements that must be met if it is to be used in an instrumentation system. These are as follows:

1. Accuracy
2. Stability
3. Reliability
4. Does not "load" the sensor
5. Provides sufficient output signal

The first three items on the list are very similar to those already described for the sensor. Without an accurately known relationship between the input and the output of the processor, the information contained in the sensor output signal would be meaningless after it passed through the processor. For the processor to be accurate it must also be stable, its input-output relationship must remain constant, and it must be reliable so it can be depended upon to carry out its function.

Since the processor is connected to the output of the sensor, this process of connection must not distort the signal produced by the sensor in any way. When distortion occurs from the connection, it is due to *loading,* and it results in additional inaccuracies being introduced into the measurement. Therefore, the processor in an instrumentation system must provide a

minimum of loading to the sensor. A simple example of loading can be considered from the circuit in Figure 1.3. Here a sensor is represented by its *Thevinen equivalent circuit*, a voltage source, $e_s(t)$, that is related to the variable being measured and a series resistance, R_s, known as the sensor's *source resistance*. When this sensor is connected to an electronic signal processor, this processor will draw some current from the sensor unless it is a very special type of processor that has been designed to not draw any current at all; a design that is very difficult to achieve in practice. The input of the processor is said to *load* the sensor, and we can represent this load as resistor R_L in the circuit if Figure 1.4.
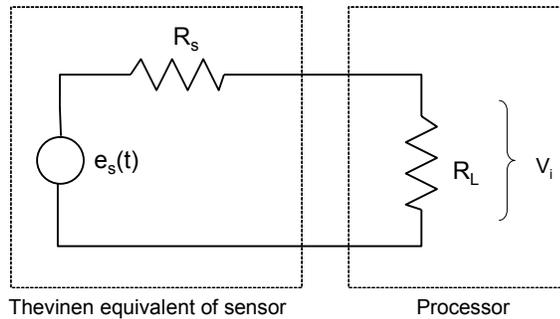

Fig. 1.3 Simplified circuit of a sensor connected to a processor.

The voltage at the input of the processor will be

$$V_i = \frac{R_L}{R_s + R_L} e_s(t) \tag{1.1}$$

As long as $R_L \gg R_s$, V_i will be very close to the desired value of $e_s(t)$, but if R_L is not very large with respect to R_s this can significantly load the sensor and result in a voltage at the input of the processor that is significantly less than $e_s(t)$. This can lead to an error in the measurement. Loading of a sensor can produce other errors. Some sensors change their characteristics when they are too heavily loaded, and this will lead to further errors in the sensor's calibration. In some cases this effect increases as the duration of the load increases, leading to even further errors. A good general rule is to use processors with very high input resistance in an effort to avoid these problems. Today, most electronic processors connected to sensors used for biomedical applications have input resistances of $10 - 1,000$ MΩ, and this is adequate for most types of sensors. There are, however, some major exceptions to this. Potentiometric chemical sensors such as the glass pH electrode that is used to determine how acid or alkaline a substance is can have source resistances in the GΩ (10^9 ohms) range. In this case, a processor consisting of an amplifier that has an input resistance of one GΩ (a very good amplifier for most applications) would result in a significant reduction in the apparent output voltage from the sensor. In this case, special amplifiers known as electrometer amplifiers that have input resistances as high as 10^{15} Ω must be used.

Finally, the processor must be capable of providing the signal required by the next block in the instrumentation system, the display and/or storage. If the output signal of the sensor is

known and the required signal to drive the storage or display is known, the processor must be designed so that it can effect the modification of the sensor output signal to provide the display or storage input signal.

The final block of the generalized instrumentation system is the display and/or storage portion of the system. The function of this block is to present and, in some cases, record data on the variable or variables being measured by the instrument system in such a way that it can be read and analyzed by a human operator or a computer. A *display* device presents instantaneous data so that it can be read from the instrument by a human, but it does not remember any of the data. Thus, a display must be continuously watched if the data is to be carefully observed. There are several types of display devices that are useful in the biomedical instrumentation. These are listed as follows:

1. *Analog scale.* A common electrical meter is an example of an analog scale. Here, some sort of a pointer indicates a location on a graduated scale calibrated in the proper units. This represents the value of the measured variable.

2. *Digital readout.* This device indicates the numeric value of a variable by having the actual numerals displayed. In some cases, letters and other symbols can also be displayed.

3. *Loud speaker* or *other sound source.* This device can indicate by means of generating sound waves. Some instruments even use an artificial voice generated by a computer to announce the results of a measurement.

4. *Cathode ray tube or flat panel solid state display.* This familiar picture tube or LCD readout of a television set or a computer monitor can display complete photographic-quality images, graphical data, and other computer generated illustrations and text material.

5. *Indicator lamp* or *Light Emitting Diode.* These are binary or "go-no-go" displays in that they can only indicate one of two states: light on or light off. Some light emitting diodes can also change color based on the input signal.

Examples of the above mentioned display devices are illustrated in Figure 1.4.

Storage devices differ from display devices in that they keep a permanent record of all data. This record may appear as a chart, a printed page, or invisible electrical, optical or magnetic signal. Examples of storage devices are shown in Figure 15 and listed below.

1. *Chart recorders.* Graphic data is permanently plotted by these devices. There are several types of chart recorders:

a.) *Strip chart recorder. A* variable is plotted on a long, narrow strip of graph paper that is moved past the plotting mechanism such as a pen, at a uniform rate thus giving a graph of the variable as a function of time.

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b.) *Trend recorder.* This is very similar to the strip chart recorder, only that the time scale is very long, and that several hours of data can be placed on a single 8 ½" x 11" sheet of paper, thus making it possible to easily observe long term trends in the data.

c.) *Event recorder.* This recorder, again is similar to the strip chart recorder, instead of recording the actual numerical value of a variable, it records only two states, "on" and "off". Thus it can only be used to record the occurrence of a particular event, denoted by the "on" position, or the lack of that event by the "off" position.

d.) *X - Y recorder.* Instead of using time as one axis, this recorder plots a two-dimensional graph with two variables being measured, one on the x-axis and one on the y-axis. This allows interrelationships between the two variables to be easily visualized.

2. Magnetic Recording. Data can be recorded by means of magnetic fields on tapes or discs of special magnetic material. This data can then be played back to reproduce the original signal.
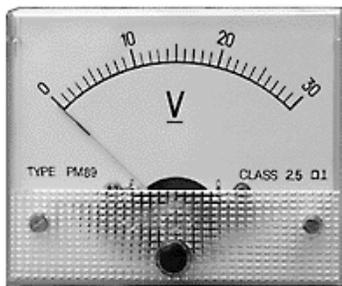
A   B

C

Figure 1.4. Examples of display devices: (A) Moving pointer meter, (B) Digital display and (C) Cathode ray tube display (computer monitor).

3. *Photographic Recording.* Either still or motion pictures can be taken of display devices indicating data for a permanent record of that data.

4. *Printer.* Computer generated data in either alphanumeric or graphic format is transferred to paper or other tangible material such as polymer film by this device.

5. *Electronic Memories.* Special electronic devices and circuits can be used to remember data. These memories can then recall their data upon command to be shown on a display device, and then can be instructed to forget the data and memorize new data. A large amount of information can be stored on a very small integrated circuit chip using this approach.

6. *Computer data acquisition systems.* Some of the previously listed storage devices can be included in a computer system that in addition to processing the data, stores it internally in random access memory (RAM) on the system disc or on specific archival memory devices such as magnetic discs, magnetic tapes or optical media such as CD ROM or DVD discs.

The display and storage block of our generalized instrumentation system has similar requirements to the other blocks. These are listed as follows:

1. Accuracy
2. Stability
3. Reliability
4. Readabiliy

Accuracy, stability and reliability have been previously discussed. The readability problem is an important one. It is necessary for display and storage devices to be able to present the data that they are indicating in understandable form. For example, if a display device is to indicate physiologic information for personnel in an operating room, it must present this information in such a way that it is easily observed and understood from all parts of the operating room. This means that if it is a digital type display, the numerals must be sufficiently large that they can be read at a glance from across the room. The digits must not change too rapidly lest they be confusing. The data must also be presented or stored in a form that will be useful for further processing. This means the data that is recorded for playback at a later time must be recorded so that it can be played back in a way that provides a signal that is as useful as the original data. It is, therefore, important to choose the recording or storage device according to the type of data that is to be recorded or stored.

In previous pages we have looked rather superficially at the blocks of a generalized instrumentation system. It will take the remainder of this course to become specific about what fits into these blocks.
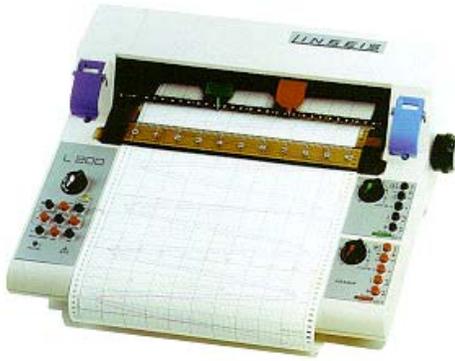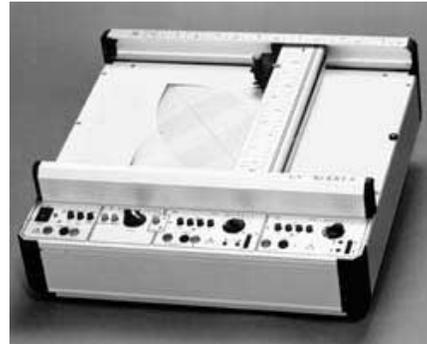
Figure 1.5. Storage Devices: (A) Strip chart recorder or recording oscillograph, (B) Digital printer, (C) Event recorder, (D) X - Y plotter, (E) electronic memory and (F) Magnetic tape recorder.

1.3 GENERAL CONCERNS FOR INSTRUMENTATION SYSTEMS

In designing instrumentation systems for use in biomedical (and other) systems, there are several considerations that must be taken into account. One must be first concerned with the overall accuracy and precision of the system. The requirements of the specific variable being measured determines the necessary *accuracy* for the instrument. If it is necessary to know the sound intensity in a room to within ± 5% of its true value, it is important to use a sound intensity meter that has an accuracy that yields errors of less than ± 5%. Sometimes it is not necessary to know the value of a variable accurately, but it is important to be able to correctly measure very small changes in this variable. To do this, then, a high *precision* instrument is required. Even if the accuracy of our sound intensity meter is only ± 5% (really, we should say the accuracy is 95%, since it is the error that is 5%, but most people refer to the accuracy

of an instrument by stating the error), if it has a precision of 1% of the total intensity, then we can measure changes in the sound intensity much more accurately than we can measure the total sound intensity.   The smallest change in a measured variable that can be detected by the instrument is known as the *resolution* of the instrument. It is another important term for describing instrumentation. The resolution tells us how close two different measurements of a variable can be yet we can still tell that these measurements are different.

To understand the overall accuracy and precision of an instrument we sometimes look at a quantity known as its transfer function. This may be illustrated by the generalized instrument of Figure 1.6.
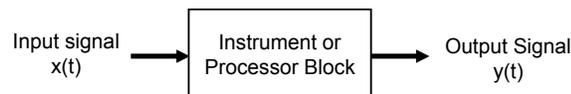

Figure 1.6. General instrument block for defining the transfer function.

This instrument has some time varying input, namely, the variable being measured which we shall denote by x(t) and some output that we shall denote by y(t). In the case of our example of the sound intensity meter, the input x would be the sound in the room being measured, and our output would be indication on the display device. The transfer function of the instrument describes what happened to the input x(t) to get the output y(t). This can be described mathematically by the equation:

$$y(t) = T\,[x(t)] \tag{1.2}$$

where T is the transfer function of the instrument. For an instrument with good accuracy and precision the transfer function must be well defined and stable. Later on we will find this concept of transfer function especially useful in describing the processor block of an instrument system.

Another factor that is essential in describing the overall accuracy and precision of an instrument is its *fidelity.* For an instrument to accurately measure a variable, it must be able to follow changes in this variable over the course of time. As in a high fidelity home music system, the instrument must be able to faithfully reproduce the variable that it is measuring. We will find that this means that we must know the maximum rate of change of the variable to be measured and its frequency spectrum, so that we can specify the proper instrument to do this job.

Another important consideration in determining the accuracy of an instrumentation system is the method of its calibration. A highly stable system need not be calibrated very often; however, for the highest accuracy it must be calibrated with an established standard. The procedure of calibration consists of measuring the standard with the instrument and then

adjusting the instrument so that it reads the known value of the standard. The value of the standard should be known to at least the same *accuracy* as that of the instrument to be calibrated. If the measurement is to be taken immediately after the instrument is calibrated, a standard having a known value to at least the rated *precision* of the instrument may be used to improve the accuracy of the instrument. In the case of this measurement, the instrument will be as "accurate" as its "precision".

An important consideration in determining the amount of calibration required for a particular instrument is its stability. An instrument that presents a great amount of drift will have to be calibrated several times throughout the period of time in which it is used while one that is relatively stable need only be calibrated once.

Another factor that is closely related to the accuracy and precision of an instrument is its *signal-to-noise* ratio. We can define the *signal* as the information about the actual variable being measured by the instrument, and the *noise* as all other signals that are observed on the instrument display. Thus, if we can make our signal zero (make sure that the variable being measured by the instrument is zero) then everything that is displayed by the instrument will be noise. When there is a signal present, this noise can interfere with the signal to reduce the accuracy and precision of the instrument in observing that signal. The signal to noise ratio is a useful quantity to tell us how much noise is present with respect to the signal being measured. We can define the signal-to-noise ratio by means of the simple equation:

$$Signal-to-noise\ ratio = \frac{Signal\ power}{Noise\ power} \qquad (1.3)$$

For highly accurate measurements, an instrument must have a signal-to-noise ratio that is a large number such as 10,000. As a means of presenting this number in a more readable format, we often present signal-to-noise ratio using a logarithmic scale. Electrical engineers have borrowed the logarithmic scale used to measure sound intensity to do this. Signal-to-noise ratios are usually presented using the *decibel* scale. Equation (1.3) becomes

$$Signal-to-noise\ ratio = 10\log_{10}\left[\frac{Signal\ power}{Noise\ power}\right] \qquad (1.4)$$

In biomedical instrumentation, we often speak of signals in terms of the voltage of that signal. Since in electrical terms we can determine power by

$$Power = \frac{V^2}{R} \qquad (1.5)$$

we could substitute equation (1.5) into equation (1.4) to get the signal-to-noise ratio in terms of voltages that we might measure in an actual instrumentation system.

$$Signal-to-noise\ ratio = 20 \log_{10}\left[\frac{Signal\ voltage}{Noise\ voltage}\right] \qquad (1.6)$$

This is generally the way that instrumentation engineers present signal-to-noise ratio today. Voltages are much easier to measure than powers, and so when a biomedical instrumentation engineer refers to signal-to-noise ratio, she is usually referring to equation (1.6).

Signal-to-noise ratio is a very important concept in instrumentation systems. Although in the past we were primarily concerned with the sensitivity of an instrument, now that high-quality amplifiers are available to boost the strength of very weak signals, this is no longer a major concern. Instead we need to know what the relationship between our signal and the noise might be. We can always amplify a weak signal, but if it is buried in noise, we will also amplify the noise. The signal-to-noise ratio will remain the same! Amplifiers in general introduce some noise themselves, so the signal-to-noise ratio might even be lower after the amplification process.

We will look at this quantity in more detail when we discuss the measurement of biopotentials and will see some examples of its use at that time.