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Clinical Laboratory

Little, Brown and Company · Boston

Library of Congress catalog card No. 72-155031

First Edition

ISBN 0-316-00643

4138-10G1-M01/72

Published in Great Britain
by Churchill/Livingstone, Edinburgh and London

Printed in the United States of America

Electronic Instrumentation in the Clinical Laboratory

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Preface

Instruments used in the clinical laboratory are becoming increasingly complex in design, and many new types are introduced each year. Even the simplest spectrophotometer may now contain relatively sophisticated electronic circuits. These factors increase the problems encountered in equipment operation and maintenance. Even the laboratory director may not understand well the theory of operation of all the instruments. This may make the services of an electronics expert necessary for all but the simplest maintenance or repair.

Knowledge of the elementary principles of electricity and electronics will be helpful in the use of these instruments. In addition, it will aid the laboratory worker in diagnosing the simpler causes of instrument malfunctioning, in understanding the rationale of the troubleshooting tests suggested by the manufacturers' instruction manuals, and in determining the types of malfunctioning in which these tests are applicable. If the services of an expert are required, valuable time can be saved by the knowledge that the simpler causes of malfunctioning have been eliminated and the probable causes already suggested.

Some knowledge of the theory of operation will also enable the worker to use an instrument more intelligently. He will have some idea of why the suggested operational and maintenance procedures are necessary and why certain shortcuts which may suggest themselves are not applicable. A knowledge of how an instrument works will give the worker some basis for appreciating its particular advantages and limitations. Too often the laboratory worker regards the instrument as a mysterious "black box" in which the sample is inserted at A and the answer comes out at B. If the answer does not come out as scheduled, the worker should be able to do more than wring his hands in despair.

The fundamental approach of *Electronic Instrumentation in the Clinical Laboratory* is that practically all the instruments discussed are used to measure a concentration of some substance (usually in solution) in one form or another. This concentration is related by some means to an electrical current or potential. The magnitude of this electrical component is determined as a measure of the concentration of the test substance. Different types of instruments may use various ways of relating the concentration to the electrical signal or of measuring the electrical signal obtained.

The text covers several areas. After a review of the fundamentals of electricity and electrical measurements, the nature of light, light production, and light measurement are treated in some detail. Most laboratory tests involve instruments that use the measurement of the emission or absorption of light to determine concentration. The theory of the operation of the various types of these instruments is discussed. Included are colorimetry and photometry, flame and atomic absorption photometry, and fluorometry. The discussion includes mention not only of the purely electrical or electronic phenomena involved, but also other physical or physiochemical principles required for a complete understanding of the operation of the instrument. Only slight mention is made of the purely chemical aspects which are discussed in most laboratory manuals.

Other methods which do not use light are discussed next. These include specific ion electrodes, electrophoresis, chromatography, conductivity and osmolality determinations, and particle and radioactive counting. Here also the discussion includes not only the purely electrical theory, but also other principles necessary for the understanding of the operation and use of various instruments.

The second major area deals with the theory of operation of vacuum tubes and semiconductors and their use in the various types of circuits found in instruments. The types of circuits include voltage supplies, amplifiers, oscillators, and counting circuits. Sufficient theoretical basis is given to enable the technician to understand the principles by which the various types of circuits operate.

I have included a short introduction to the theory of computers, which are being used increasingly in the laboratory. A brief discussion of the various types of computers which may be found or used in the clinical laboratory is given, together with some information about their limitations and capabilities.

The last chapters deal with test instruments and methods for troubleshooting for the several types of instruments mentioned. A glossary of terms and suggestions for future reading conclude the text.

Philip G. Ackermann

Acknowledgments

This book is a development of material written for use in courses in the School of Medical Technology and in the residency training program in pathology at DePaul Hospital. I express my sincere appreciation to Dr. John Bauer, Laboratory Director, for his encouragement. I also thank those who have read the manuscript and offered criticisms or suggestions for improvement, including the late Mr. Walter Elle, physicist, Isotope Laboratory, and Mrs. Mary Thorsten, Laboratory Supervisor, both of DePaul, and Dr. Gelson Toro of the Missouri Clinical and Biochemical Laboratory. I gratefully acknowledge the help and encouragement of Dr. William H. Masters, Director, Reproductive Biology Research Foundation, for his continued interest and for providing financial and secretarial assistance by the Foundation.

I also appreciate the work of Miss Marilyn Harris of the Department of Illustration, Washington University School of Medicine, in the preparation of the illustrations, the encouragement and assistance of Mr. Fred Belliveau and Mr. William Decker of Little, Brown and Company, and the invaluable assistance of Miss Julie Hendryx, Mrs. Ruta Vietmanis, Miss Sandra Hackman, and Mrs. Muriel Thompson in the final preparation of the manuscript.

I am grateful for the permission granted by some manufacturers (particularly Instrumentation Laboratory, Orion Research, G. K. Turner Associates, Bristol Division of American Chain & Cable Company, and Beckman Instruments) to use material provided by them and I appreciate the information sent by other manufacturers concerning their instruments. Some of the illustrations in the text were taken from the Armed Forces textbooks mentioned in the suggestions for further reading. These sources are acknowledged with gratitude.

Above all I am very grateful for the continued encouragement by my wife Momoyo whose moral support and tolerance of my neglect of other duties for work on the manuscript made this book possible.

P. G. A.

Electronic Instrumentation in the Clinical Laboratory

Contents

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General Principles of Electricity

Nature and Flow of Electricity

It has been known since early times that when a glass rod is rubbed vigorously with a piece of silk, the rod will acquire an electric charge. If an amber rod is rubbed with fur (cat's fur was usually specified), the amber will acquire an electric charge that is different from that on the glass rod. These two different types of charges attract each other. The kind of electricity found on the glass rod was called positive; the other type, negative. The name *electron* for the elementary negatively charged particle is derived from the Greek word for amber. The convention was adopted to consider the flow of an electric current as the flow of positive electricity. We know now that an electric current is actually the flow of negative electrons. Thus, the flow of electrons is in the opposite direction to that of the conventionally described positive current. The older convention is still used in the description of electric circuits, but it must be remembered that the actual flow of electrons is in the opposite direction. Since the electrons are mobile portions of the atoms, anything with a positive charge—a glass rod, for instance—merely has a deficiency of electrons (some electrons were removed from the glass by friction), leaving a net positive charge. Anything with a negative charge merely has an excess of electrons over those required to neutralize all positive charges.

An electric current generally consists of a flow of electrons through a wire or other medium. Matter (atoms) is composed of relatively large positively charged particles (atomic nuclei) surrounded by small negative electrons. Many solids consist of atoms or molecules arranged in a regular array or crystal lattice. In some solids a few of the electrons are relatively loosely bound to the nuclei and can move fairly freely through the lattice under the influence of an electrical potential. Such solids will readily conduct an electric current. Most metals belong to this class. Not all metals conduct electricity with equal ease. Silver is the best conductor, followed by copper and gold. Some metalliclike elements such as germanium and arsenic are relatively poor conductors of electricity and are often spoken of as **semiconductors.** In other solids all the electrons are more tightly bound and there are very few free electrons to conduct an electric current. This is particularly true if the solid is composed of molecules (such as glucose) rather than individual atoms (such as iron). If a solid conducts an electric current only very slightly under ordinary conditions, it is called an insulator or nonconductor. To illustrate the relative conductivity of different types of materials, if we take the specific resistance of silver as unity (the lower the resistance, the greater the conductivity), the range of resistance of ordinary conductors lies between 1 and 100, that of semiconductors (as the term is usually used) between 10^5 and 10^8, and that of good insulators between 10^{14} and 10^{30}. For most substances the electrical resistance increases with increasing temperature as long as the temperature change is not sufficient to produce any physical or chemical change in the substance (e.g., melting or decomposition).

The conductivity of aqueous solutions is of a different nature. Pure water is a relatively poor conductor of electricity. When a salt such as sodium chloride is dissolved in the water, positively charged (sodium) and negatively charged (chloride) ions are formed. These will conduct an electric current through the solution. The degree of conductivity of an aqueous solution will depend upon the number and type of ions present. As will be seen later, the conductivity of an aqueous solution can be used as a measure of the number of ions present. Solutions of nonionizable substances such as glucose do not conduct an electric current.

In an explanation of the principles of electrical circuits it is helpful to consider the analogy between the flow of water in a pipe and the flow of electrons in a conducting medium. The pressure that forces the water through the pipe corresponds to the electrical potential or **electromotive force (EMF)** that causes the flow of the electrons. This quantity is measured in **volts** (or derived units such as kilovolts or millivolts). It is usually designated by E (or e) in circuit analysis, although sometimes V is used. The resistance to the flow of water offered by the pipe, bends, constrictions, valves, etc., corresponds to the electrical **resistance** offered to the flow of electrons. The resistance is usually measured in **ohms.** In circuit analysis the resistance is designated by the letter R. In tabulating the numerical values of resistances, such as, say, 100 ohms, the Greek letter omega, Ω, is often used as a symbol of ohm.

Corresponding to the rate of flow of water through the pipe (e.g., in gallons per minute) is the electrical **current,** the rate of flow of electrons. This is measured in **amperes** (milliamperes, microamperes) and is usually designated in circuit analysis by the letter I (or sometimes i). The actual quantity of electrical charges (Q) corresponding to the actual quantity of water (gallons) is measured in **coulombs.** The coulomb is the quantity of electricity equivalent to the charge on approximately 6.24×10^{18} electrons. One ampere is the electrical flow of 1 coulomb per second. One is usually more interested in the rate of flow of electrons rather than the quantity, just as one is usually more interested in the rate at which the water comes out of the pipe rather than how much is actually standing in the pipes at any one time. Thus, the coulomb is used less frequently in circuit analysis than are the other units mentioned.

Ohm's Law

Current, voltage, and resistance are related by what is known as **Ohm's law:** $E = IR$, or: voltage = current × resistance, or: volts = amperes × ohms. This is one of the fundamental laws of electricity and holds accurately for direct current flow in conductors.

The rate at which energy is utilized or produced in the circuit—that is, the **power** input or output—is related to the above quantities by the formula: $P = EI = I^2R$, or: watts = volts × amperes. The **watt** is thus the measure of the rate at which energy is being used. A particular total quantity of energy would be measured in units such as a watt-hour, the amount of energy expended when it is used at the rate of 1 watt for a period of 1 hour. The power equation also holds exactly for all direct current circuits. It is also consistent with the hydraulic analogy; one would expect that the energy required to pump water through the pipe would increase with the rate of water flow (I) and with the resistance offered by the pipes to the flow (R).

Direct and Alternating Currents

An electrical current can be either a **direct current (dc),** in which the electrons move uniformly in one direction, or an **alternating current (ac),** in which the electrons oscillate back and forth in the conductor, moving first in one direction and then in the opposite direction. If we measure the current and voltage at a given point in an alternating current circuit, we find that both values vary with time, usually in a sinusoidal manner, as indicated in Figure 1-1. The rate of oscillation, or **frequency,** is usually expressed in cycles per second, the number of complete oscillations made in a second. Ordinary alternating house cur-

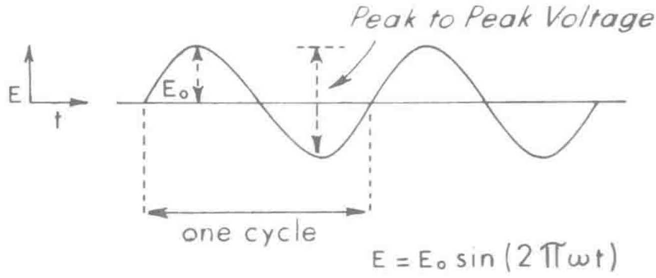

Figure 1-1

Curve illustrating a sine wave variation in voltage, showing length of cycle and definition of various quantities.

rent is usually 60 cycles per second (50 cycles in some localities). Radio waves are usually measured in kilocycles (thousands of cycles) and television waves in megacycles (millions of cycles). Recently the term **Hertz (Hz)** has been introduced for use in place of cycles per second (1 Hz = 1 cycle per second).

If the variation of voltage is expressed by the equation $E = E_0 \sin (2 \pi \omega t)$, where ω is the frequency and t is the time, we can express the magnitude of the voltage as being equal to E_0, or we can express the magnitude as equal to the peak-to-peak voltage which, as the figure shows, is equal to twice E_0. Both values are sometimes used. For commercial and other alternating currents having approximately a sine wave form, the voltage measured is usually the **root-mean-square (rms) voltage.** It is numerically equal to $\frac{1}{2}\sqrt{2}\, E_0$ for a pure sine wave. It is computed by squaring the instantaneous voltage, finding the average of the squared voltage, and then taking the square root of the average; hence the name *root-mean-square voltage.* In a direct current circuit the power (rate of energy utilization) is equal to I^2R, as mentioned earlier. To apply this formula to ac circuits we find the average power by dividing the average of the squared voltage by the resistance. Thus, the formula holds for ac currents, if we use the rms voltage. (Strictly speaking, the power formula holds for circuits containing only resistances.)

Resistances

In Figure 1-2 are given the symbols usually used for resistances in circuit diagrams. Illustrated are a fixed resistance, variable resistances whose values might change from time to time, and a potentiometer arrangement. Electrical resistances may be either wire-wound or com-

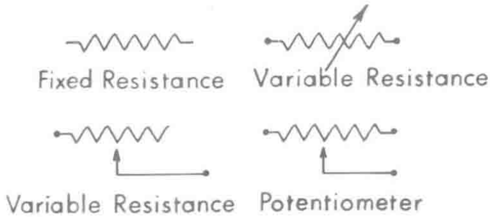

Figure 1-2
Circuit symbols for some common types of resistors.

position. The former are made by winding wire of the desired size on an insulating core. Molded composition resistors are made from a mixture containing carbon or other relatively poor conductor enclosed in an insulated case, as shown in Figure 1-3.

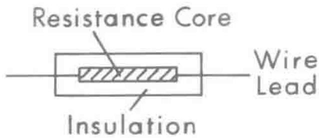

Figure 1-3
A molded composition resistor, showing the molded resistance core surrounded by an insulating layer.

Resistors are made in different current-carrying capacities. Those made to carry an appreciable amount of current are usually wire-wound. The rating is usually in watts, the amount of power that can be dissipated by the resistor. A 10,000-ohm, 1-watt resistor would have a maximum current-carrying capacity of 0.01 ampere (10 milliamperes) ($P = I^2R = 10{,}000 \times (0.01)^2 = 1$). For ordinary use in electronic circuits the resistors are made to a tolerance of $\pm 10\%$ from the nominal value. For some purposes involving measurements, closer tolerance may be required.

When two or more resistances are connected in series, as shown in Figure 1-4a, the combined resistance is the sum of the separate resistances, as might be expected: $R = R_1 + R_2 + \cdots$. When two resistances are connected in parallel (Fig. 1-4b), the combined resistance is less than that of either separately. It can be shown that as a consequence of Ohm's law: $1/R = (1/R_1) + (1/R_2) + (1/R_3) + \cdots$, or, for two resistances:

$$R = \frac{R_1 R_2}{R_1 + R_2}$$

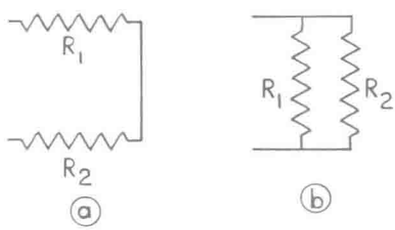

Figure 1-4
Resistances in series (a) and in parallel (b).