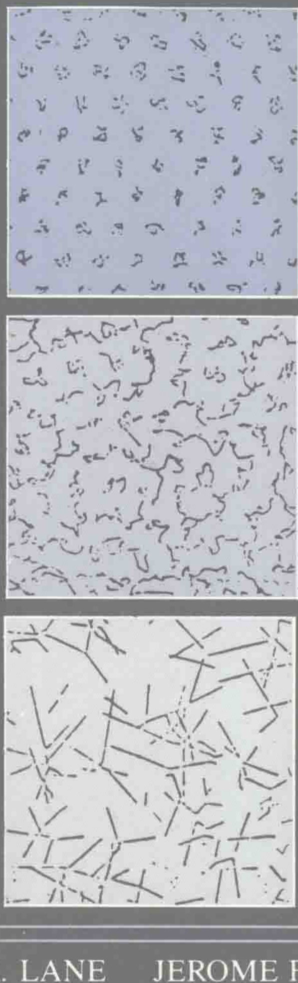
CLINICAL Arterial Blood Gas ANALYSIS



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With 79 illustrations

The C. V. Mosby Company

ST. LOUIS · WASHINGTON, D.C. · TORONTO 1987

MOSBY

A TRADITION OF PUBLISHING EXCELLENCE

Editor: David Culverwell
Assistant editor: Elizabeth Raven
Project editor: Sylvia B. Kluth
Manuscript editor: Roger McWilliams
Designer: Susan E. Lane
Production: Florence Fansher, Kathy Burmann

Printed in the United States of America

The C.V. Mosby Company
11830 Westline Industrial Drive, St. Louis, Missouri 63146

Library of Congress Cataloging-in-Publication Data

Lane, Emery E.
Clinical arterial blood gas analysis.

Includes bibliographies and index.
1. Blood gases—Analysis. I. Walker, Jerome F.
II. Title. [DNLM: 1. Arteries. 2. Blood Gas Analysis.
QY 450 L265c]
RB45.L28 1987 615.8'36 86-28477
ISBN 0-8016-2859-8

VT/VH/VH 9 8 7 6 5 4 3 2 1 04/B/517

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To

Marita Lane and **Annette Walker**

PREFACE

This book has been designed to bring together information about gas laws, acid-base physiology, and gas transport in the maintenance of normal oxygenation, carbon dioxide tension, bicarbonate, and pH. We have attempted to help the reader understand the importance of the lungs and kidneys in keeping blood gases within normal limits. Additionally, what happens to the normal person when he or she exercises or changes altitude is considered.

If the normal state can be adequately explained and understood, the reader should better comprehend variations from normal, that is, the pathophysiology of disease. We believe that all of this is necessary for clinicians to make intelligent evaluation of arterial blood gases in a given setting.

In addition, a chapter has been set aside to discuss the variables affecting measurement of arterial blood gases.

We have intended to discuss some of this rather complicated material in terms that can be understood by physicians, nurses, respiratory therapists, medical students, and others involved in clinical practice.

We wish to thank our reviewers: F. Herbert Douce, M.S., R.R.T., Respiratory Therapy Division, Ohio State University; Leona (Shelley) C. Mishoe, B.S.R.T., M.Ed., R.R.T., Department of Respiratory Therapy, Medical College of Georgia; Donald M. Shawver, B.S., M.S., Respiratory Therapy Technician Program, Indiana Vocational Technical College; Danita Turner, R.R.T., A.A.S., Respiratory Therapy School, Kansas Community College; and Barbara George Wilson, B.S., M.Ed., R.R.T., formerly of the Department of Respiratory Therapy, Santa Fe Community College, Gainesville, Florida.

We are grateful for the able editorial assistance of Rosa Kasper, David Culverwell, and Liz Raven of The C.V. Mosby Company and for the work of the artist, Jack Tandy.

Sincere thanks also go to Nancy Roubieu, Marlene Humphrey, and Becca Seitz for typing the manuscript.

Emery E. Lane
Jerome F. Walker

INTRODUCTION

EVOLUTION OF CELLS AND METABOLISM

However the Earth was created, its beginning occurred about 4.6 billion years ago when no life of any kind existed. Only after approximately one billion years did the first microorganisms appear. In the intervening time, chemical evolution had made it possible for life to begin by providing the necessary raw materials.

Initially, Earth's atmosphere was composed of gases such as water vapor, carbon dioxide, carbon monoxide, methane, ammonia, and hydrogen sulfide. These served as building blocks for the creation of life, as well as substances necessary to sustain it. Subsequently, organic bases, sugars, and amino acids were synthesized, and these simple molecules grew into primitive nucleic acid and protein chains. Concurrent development of enzymes and the evolution of what have been called *protobionts* ensured survival of the life process. Protobionts are identifiable chemical units capable of reproduction. The further development of cell walls and increasingly sophisticated subcellular units enhanced identity of cells, their reproductive capacity, and continuing evolution.

At this time, molecular oxygen could not have existed in a significant amount since the developmental processes just described could not have taken place in an oxygen-containing atmosphere: "Oxygen is a dangerously corrosive and poisonous gas, from which human beings and other organisms are protected by elaborate chemical and physical mechanisms" (Dickerson, 1978).

Simple addition of electrons to oxygen (O_2) unleashes free radicals that may injure subcellular structures, killing cells. However, the early development of enzymes (for example, superoxide dismutase, catalase, and peroxidase) provided protection from the high potential energy of O_2.

Most O_2 is stored with carbon dioxide (CO_2) and carbon monoxide (CO) in sedimentary rock so that very little of this gas is present in Earth's atmosphere. No primary source of O_2 exists. However, in the presence of ultraviolet radiation from the sun, O_2 is produced in the Earth's outer atmosphere by breakdown of water vapor and is manufactured from water vapor and CO_2 in the process known as photosynthesis:

$$H_2O + CO_2 \xrightarrow{\text{ultraviolet}} CHO + O_2$$

This yields carbohydrates (CHO). It is a reversible process that stores energy.

Photosynthesis first evolved in blue-green algae (Cyanobacteria), many examples of which still exist. Some are not tolerant of O_2, but others have developed an ability to exist in an atmosphere containing significant concentrations of O_2. However, about 1.3 billion years passed before multicellular animal life or plant life could be sustained (Campbell, 1982).

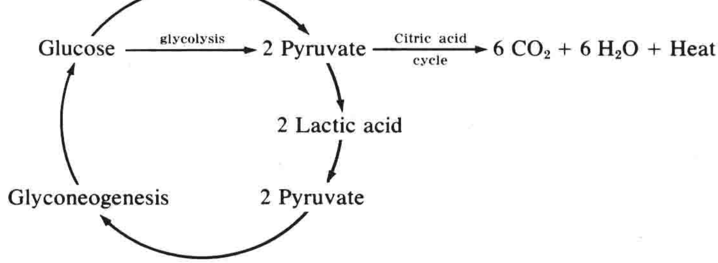
Other cells depended on their capability of metabolizing substances from their environment. They developed processes of metabolism by which carbohydrate compounds such as glucose could be used. One such process is fermentation:

$$\text{Glucose} \xrightarrow{\text{glycolysis}} \text{2 Pyruvate} \rightarrow \text{2 Ethyl alcohol} + CO_2 + \text{Heat}$$

A second is anaerobic metabolism:

$$\text{Glucose} \xrightarrow{\text{glycolysis}} \text{2 Pyruvate} \rightarrow \text{2 Lactic acid} + CO_2 + \text{Heat}$$

These metabolic processes use two high energy phosphate bonds and produce four. This provides usable energy to cells but is much less efficient than aerobic metabolism:



Note that the glycolytic pathway is identical in all three metabolic processes, so that each results in a net gain of two phosphate bonds and each produces pyruvate. But in aerobic metabolism, pyruvate is used as a substrate in a series of reactions called the citric acid cycle, in which six O_2 molecules form 34 phosphate bonds (for a total of 36). Thus aerobic metabolism produces 18 times as much useful energy as anaerobic metabolism. When the body's cells become deprived of O_2 because of a decrease in supply or because of increased demand, as in high levels of exercise (discussed at greater length in Chapter 7), they are able to temporarily switch to anaerobic metabolism. Doing so, they revert to the more primitive and much less efficient system of our unicellular ancestors who lived in a world without oxygen (Krogh, 1968).

From an evolutionary standpoint, it appears that gradually increasing availability of oxygen offered the advantages of greater energy production (Schopf, 1978). In addition, it made possible mitosis—a new means of replicating cells, which led the evolutionary way to multicellularity. Mitosis requires at least low concentrations of oxygen. Replication of cells in a multicellular plant or animal permits the organism to live longer and to be larger and more stable; and since cells can differentiate and become specialized, the organism is able to evolve, enabling it to live in most environments and to accommodate to environmental changes. Since many cells can be devoted to reproduction, the organism is able to produce offspring with the same capabilities as the parent (Valentine, 1978).

We humans are newcomers to the overall evolutionary scheme. But the various interrelated systems that permit our survival have evolved over billions of years from a beginning in what has been termed a "primordial soup" through development of unicellularity and multicellularity. Eventually, our ancestors appeared.

Humans possess a complex network of systems that interrelate in an intricate manner, maintaining an internal milieu which permits survival in a necessary yet somewhat hostile environment. We have a respiratory system that permits us to acquire oxygen and, by means of appropriate enzymes, to use it without harm to our cells, and then to rid ourselves of that waste product of aerobic metabolism—carbon dioxide. To complement the respiratory apparatus, there is a cardiovascular system that pumps blood to and from the lungs, from and to the tissues. Blood is another organ or system that contains a complex plasma and various kinds of cells: white blood cells that help protect us from environmental pathogens and red blood cells that transport oxygen and carbon dioxide. We also possess a urinary system whose principal organs, the kidneys, excrete certain waste products and also assist the lungs in maintaining a delicate acid-base balance (see Chapter 6). A gastrointestinal system is present; it takes in vital nutrients and provides mechanisms for absorption, metabolism, and excretion of solid wastes. The human body also contains an endocrine system that produces hormones which permit us to be conceived, grow, differentiate, and survive. Watching over and controlling all of these is a nervous system, including a brain, which, in addition to neural regulation, gives us the ability to understand a great deal about ourselves and our environment.

Chemical and cellular evolution have brought about efficient forms of metabolism—the process that has permitted human development and survival. Still, cells can revert from aerobic to anaerobic metabolism, although only at considerable expense. The chapters that follow deal with oxygen and carbon dioxide—the gases of metabolism.

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CHAPTER 1

This chapter will consider:

- **The molecular configurations of solids, liquids, and gases**
- **Physical properties of gases: their velocity, mass, and acceleration**
- **Kinetic molecular theory and gas mass-velocity relationship to energy formation**
- **The relation between kinetic molecular theory and gas pressure**
- **The relation between gas molecular activity and gas temperature**
- **Derivation of the ideal gas law: interrelationship between gas volume, pressure, and temperature**
- **Applications of the ideal gas law: Charles's law, Gay-Lussac's law, Avogadro's law, and Boyle's law**
- **The atmosphere, its gases, and computation of gas partial pressures**
- **Henry's law and gas-liquid solubility**

CONTENTS

PHYSICAL LAWS RELATED TO GAS BEHAVIOR IN THE ATMOSPHERE

To understand pulmonary structure and function and blood gases, it is appropriate to consider how gases behave in our natural environment—the atmosphere. Gas molecules form a blanket surrounding Earth to an altitude of approximately 1200 miles. In contrast to solid or liquid matter, gas molecules move freely and randomly about the atmosphere, frequently colliding with each other and with any solid or liquid objects they encounter. Gas molecules are greatly separated from one another; that is, the mean distance between them is much greater than their molecular size (Figure 1-1).

PROPERTIES OF GASES

Gas molecules have several properties. First, they are in constant motion and have velocity (v), which is defined as a change in space (s) per unit of time (t):

$$1. \quad v = \frac{\Delta s}{t}$$

Gases move very rapidly. Room temperature oxygen (O_2) has a velocity of 4.82×10^4 cm/sec, which is about 1000 miles an hour (Masterson and Slowinski, 1969).

Gas molecules also possess mass (m), the unit for which is typically the kilogram (kg), a weight measure. Mass differs from weight (W), however, because weight depends on the force of gravity (G):

$$2. \quad W = mG$$

Mass was originally defined by Isaac Newton in the seventeenth century, although inertial mass was later quantified by Ernst Mach (Dillon, 1983).

When force of sufficient magnitude is applied to a mass, acceleration (a) results. Acceleration is change in velocity over time:

$$3. \quad a = \frac{\Delta v}{t}$$

For example, because of gravity, acceleration of a falling object is 32 ft/sec^2.

Force (F) equals mass times acceleration (Newton's first law):

$$4. \quad F = ma$$

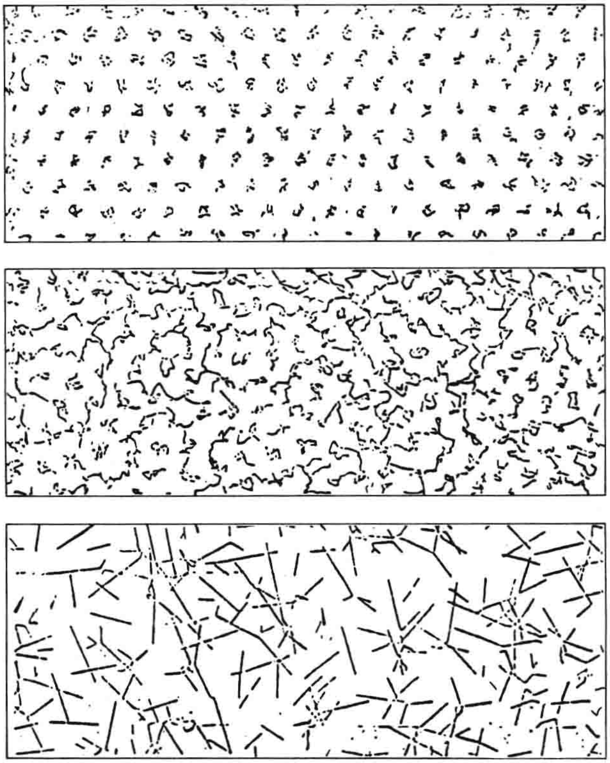

FIGURE 1-1

Trajectories of molecules in a solid (*top*), a liquid (*middle*), and a gas (*bottom*) simulated with the aid of a computer. In the solid the molecules are constrained to vibrate about fixed lattice sites, whereas molecules in the liquid and the gaseous phases are free to wander. The only substantial differences between gas and liquid states are density and frequency of collision. The simulation was done by Farid Abraham of the International Business Machines Corporation in San Jose, Calif. (From Barker, J.A., and Henderson, D.: Sci. Am., November 1981, p. 130 [with permission].)

Mach, in his inertial mass experiment, placed two objects of different mass on a frictionless plane (Figure 1-2). Compressing a spring between them, he simultaneously released the objects; the spring recoiled to its resting position. Acceleration resulted with the two objects moving in opposite directions. Since F_1 exerted on the first object (m_1) must, according to Newton's third law, be equal to that force F_2 exerts on m_2:

$$5. \quad F_1 = m_1a_1 = F_2 = m_2a_2$$

Applying Newton's second law:

$$6. \quad m_1 = m_2\frac{a_2}{a_1}$$

Therefore, mass may be defined in terms of a weight standard, and a comparison with any other mass can be made based on relative accelerations, given the same force. Gas molecules, although minuscule, have mass ranging from 10^{-23} to 10^{-20} g (Spearman and Sheldon, 1982).

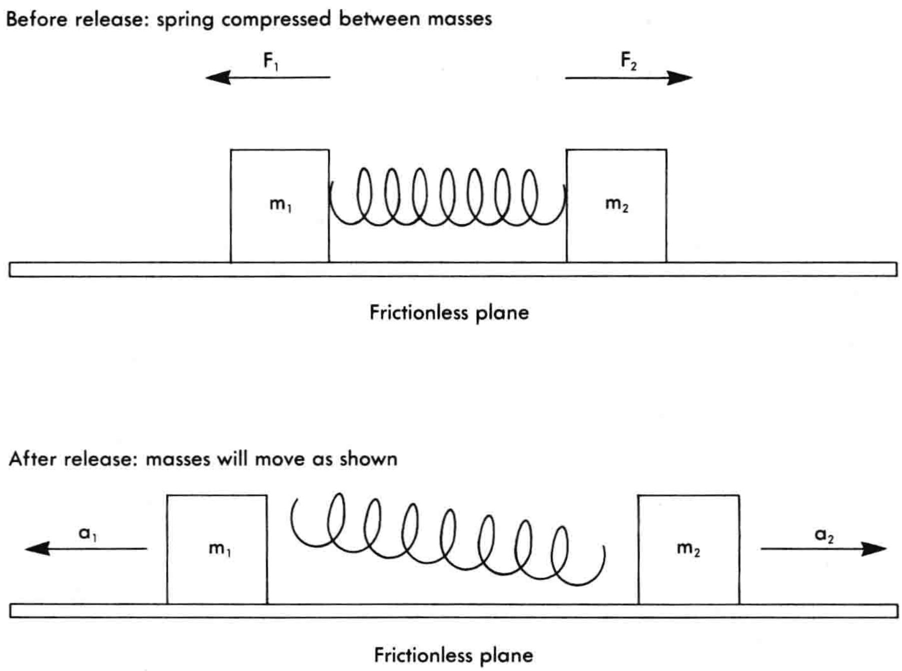

FIGURE 1-2

A version of the Mach experiment for measuring inertial mass. (From Dillon, J.A.: Foundations of general system theory, Seaside, Calif., 1983, Intersystems Publications [with permission].)