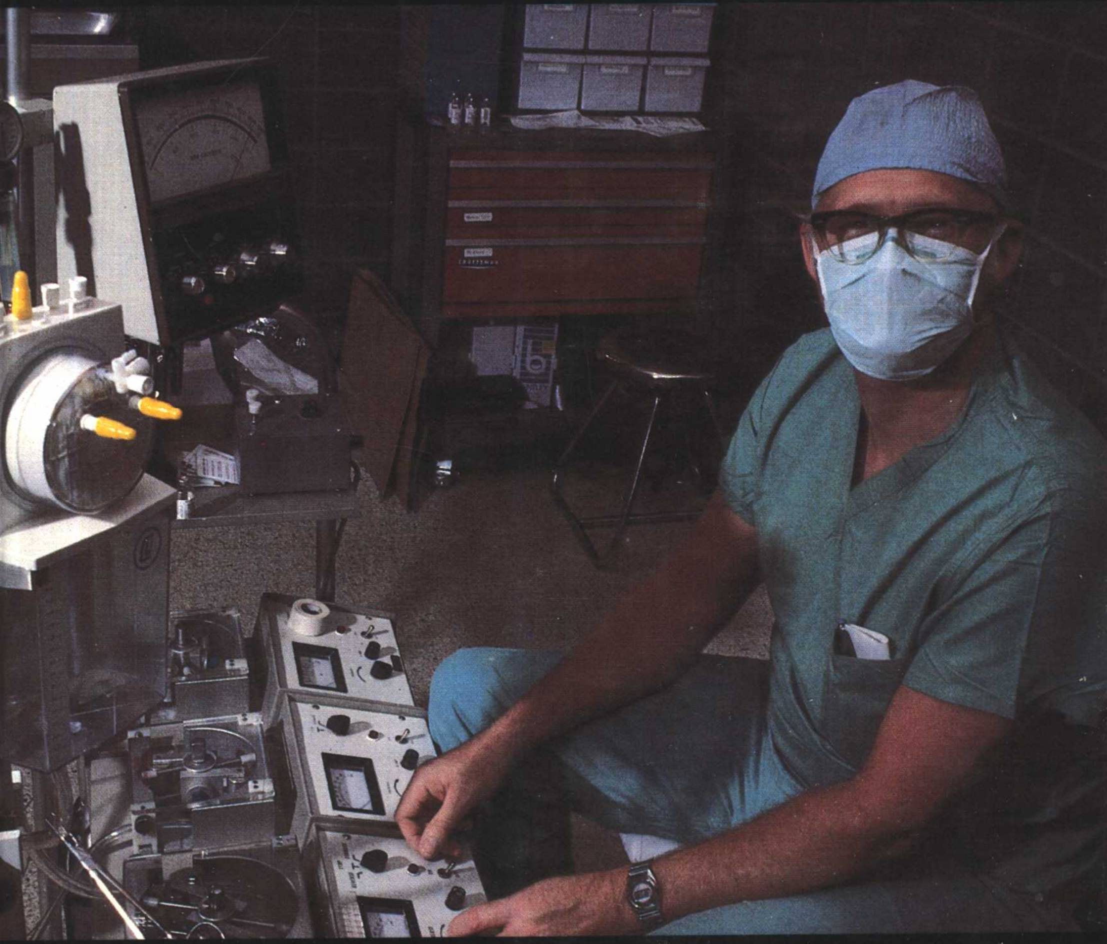

The physiology of ADEQUATE PERFUSION

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THE PHYSIOLOGY OF ADEQUATE PERFUSION

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THE PHYSIOLOGY OF ADEQUATE PERFUSION

To my wife,

AUDREY

who loves me in spite of my faults,

and to

Dick, Nancy, and Mary

my children, who accept me as I am.

Preface

This work is meant primarily as a guide for those with a fledgling interest in perfusion—students, equipment and technical representatives, and people in peripheral disciplines—and it should provide sufficient depth to be of interest to the veteran perfusionist. It should also serve to introduce the field of perfusion with its intricacies and "worries" to others related in any way to perfusion patients, such as intensive care nurses, respiratory therapists, operating room personnel, and critical care nurses, as well as those who see the patient diagnostically in the catheterization laboratory or in radiology.

This book began as a simple exercise to put down in some order all the miscellaneous bits and pieces of perfusion lore that have filled my head, desk drawers, and closet these past 20 years. This volume is the result of my effort to bring more logical order and greater understanding to my notes. The goal was to compile a primer of basic information that would prepare the reader to delve further into the fascinating study of perfusion physiology.

The presentation is laid out in major topical sections to organize those concepts that are synergistic. The problem of best placement of acid/base balance was resolved by dividing this subject into two sections located in the respiratory component of oxygenation and the metabolic component of tissue metabolism. An understanding of each separate component should aid in the digestion of the total concept.

The material included was selected to collect in one place some of the information specific to perfusion and cardiac surgery patients. The bibliography includes all the texts consulted in the preparation of the manuscript as well as some additional material, which increases the readers' perspective by treating the same subjects somewhat differently. The appendices contain a glossary, a list of normal values, a listing of selected drugs, and a "cookbook" for bubble oxygenators.

This book is not intended as a compendium on perfusion like that of Galletti and Brecher in the 1950s. It would take several volumes, each larger than this, to contain all that is pertinent about cardiac anatomy, cardiac surgery, the equipment, and the techniques. A favorable response to this volume may be motivation to undertake that monumental chore.

What is contained herein is not the final word. It is a consensus of contemporary practice. Points of disagreement will hopefully serve as a challenge to delve further into those subjects.

There are several people without whose assistance this manuscript would not have been possible, and to them I owe my undying gratitude. Dr. Tom Koelz, from our department of anesthesiology, who acted as my physiologic "devil's advocate" to prevent me from committing medical heresy, I will never be able to thank sufficiently. My dear and talented friend, Bruce Bentzen, was responsible for the illustrations. If a picture truly saves a thousand words, then you, dear reader, are probably as grateful to Bruce as I am. The many hours of typing and retyping that fell to my wife, Audrey, can never be fully compensated, but she always faced them so cheerfully that I have a feeling she has some ideas for settling the score. Whatever boons she has in mind, she has earned them under the most trying conditions (i.e., working with me) and is certainly most deserving. I am grateful to Dr. Warren Zapol in the Department of Anesthesiology at Massachusetts General Hospital in Boston for his prepublication review of the manuscript and numerous recommendations. Finally, there is the gang from Room 12, the surgeons, anesthesiologists, nurses, and technicians who have created a spirit and an environment in which work is a pleasure. To all of these dear friends, my thanks for helping make my life a joy.

All who read this volume are urged to provide their candid appraisal and recommendations for presenting a sufficient introduction to perfusion physiology.

Edward C. Berger

Introduction

Perfusion is the circulation of blood through the tissues of the body. It is the natural function of the circulatory system in concert with ventilation and respiration. Perfusion may be maintained artificially when it is necessary to intervene surgically for repair of the system.

A normal resting individual will circulate from 2.5 to 4.5 liters of arterial blood per minute for each square meter of body surface area. This is his *cardiac index*, a standardized representation of the volume of blood pumped by the heart per minute in relation to the individual's body surface area. From this arterialized blood, 23% of its oxygen will be extracted and used for metabolism. Adequate perfusion is the circulation of sufficient blood to all cells, well-oxygenated and laden with nutrients and regulatory hormones to meet the needs of cell life and remove waste products from the cells.

The cells are all contributing parts of the body's great biochemical works. The chemical reactions by which they function are affected by temperature, by acid/base levels, by energy, and by catalysts. To maintain control over the rate of the metabolic chemical reactions of the body, man maintains a constant temperature (37° C), a constant acid/base balance (pH 7.40), converts nutrients to energy, and supplies catalytic enzymes in response to body needs.

Adequate perfusion is often dependent on other, more indirect factors. It is an art trying to be an exact science. A well-developed and highly communicative liaison should exist between the anesthesiologist and the perfusionist during the perfusion. Each is dependent on the other as a member of the total patient-support unit. The relaying of information and the discussion of problems are vital to the patient's well-being. The anesthesiologist and perfusionist can be each other's best friend or worst enemy in the achievement of adequate perfusion. Actually, the patient-support team is working together to achieve not just *adequate* perfusion but *ideal* perfusion, no matter how elusive it may be in the present state of the art.

In this discussion, it is my aim to put together basic physiologic information as it relates to perfusion to reach a better understanding of *what is adequate perfusion.* The material is organized under the following five subject headings: oxygenation, tissue metabolism, hematologic considerations, hemodynamic considerations, and the effects of perfusion.

Contents

PART ONE

Oxygenation

The process of respiration, which is necessary for life in all living things, may be defined simply as the exchange of gases (primarily oxygen and carbon dioxide) between living cells and the atmosphere. It is a very simple process in single-celled animals, but a rather elaborate apparatus is necessary in the more complex animals and humans.

The respiratory system is responsible for getting oxygen from the air around us into every cell of our bodies. Similarly, it is also responsible for the removal of carbon dioxide produced in the cells and expelling it into the atmosphere. In serving these functions, a critical unit of the respiratory system is the lung—a composite organ built of airways, gas-exchange surfaces, and vessels for the circulation of blood. It is the blood, the transportation system of the body, that carries the oxygen and carbon dioxide between the lungs and the cells.

Over the years, the terminology of respiration has become rather colloquial and, therefore, requires defining. The following terms are often mistakenly used interchangeably. *Oxygenation* has become the popular term of reference for what is really meant to be gas exchange. The act of moving gases in and out of the lungs (or gas exchange device) will be called *ventilation*, whereas *respiration* will denote the utilization of oxygen and the production of carbon dioxide at the cellular level.

When the natural functions of the heart and lungs are artifically replaced, the processes of introducing oxygen to the blood and removing carbon dioxide are altered. Gas exchange takes place in an artificial oxygenator. The venous blood is exposed to higher concentrations of oxygen flowing at a rate sufficient to provide adequate oxygen uptake while sweeping away the proper amount of carbon dioxide.

First, we will examine the natural lung and its function.

RESPIRATORY ANATOMY AND MECHANICS

The nose has two nostrils (or nares) at the entrance to the two main nasal passages that, along with the mouth as a third passageway, lead to a singular collecting chamber, the pharynx. Located along these nasal passages are the olfactory organs, which sample the air and sense the odors of substances in the immediate environment.

In addition, the nasal passages have hairs to filter, mucous membranes to humidify, and the highly vascular surfaces of the nasal turbinates to warm the incoming air. A similar service is provided by the mucous membrane of the mouth, although the mouth is less of a filter in that it only traps the particles that will adhere to the sticky surfaces. Particles that are filtered by the nasal hairs and mucous membranes are blown away.

The pharynx (throat) acts as a collection point for incoming air and funnels it into the main air conduit (trachea) to the lung. The entrance to the trachea is guarded by a trapdoor valve, the epiglottis. When food or liquids are swallowed, the epiglottis closes to prevent the entrance of foreign substances into the trachea. Should some foreign material enter the trachea, the immediate reflex is to cough. If a large amount should enter, the individual may choke (have an obstructed pharynx or trachea), and suffocation may then ensue because of the lack of ventilation.

The trachea carries air from the pharynx well into the chest cavity where it divides into the left main stem bronchus serving the left lung and the right main stem bronchus serving the right lung. These main bronchi quickly branch again. The right main bronchus divides into three smaller bronchi, one for each of the three lobes of that lung; the left main bronchus divides into bronchi for each of its two lobes. These bronchi branch again and again to a total of twenty to twenty-two bronchial branchings. Almost a million smaller branches (bronchioles) arise from these bronchi. Bronchioles are small air tubes that lead to the clusters of air sacs (alveoli) in the lung.

An alveolus is a thin-walled air sac. Its wall is only about 0.1 micron (μ) thick but is filled with capillary blood vessels. The diameter of the sac varies from 75 to 275 μ. Alveoli number an estimated 3 million and are the primary organs of gas exchange between the atmosphere and blood.

These numerous alveoli have a combined gas-exchanging surface area of about 70 square meters (m^2), roughly forty times the surface area of the adult human body. The network of tiny capillary blood vessels that permeate the alveoli likewise have a surface area of 70 m^2. Capillaries have a wall thickness of 0.1 μ.

Both the bronchial air-handling system and the pulmonary blood-handling vascular system have been designed to provide huge surface areas with a minimum of resistance to flow and require low volumes.

The air passage system, as seen in Fig. 1-1, is a singular system. The same channels that carry fresh air into the lung also serve to carry the "used" air out. This is totally different from the dual system of blood vessels which transport blood through the lung. Venous blood is pumped from the right ventricle to the capillaries of the alveoli by way of the pulmonary arterial vessels that bring blood to the lung. After the venous blood has passed through the alveolar capillary bed and become oxygenated, it is carried by a different network, the pulmonary venous system, to the left atrium for eventual distribution to the body. Veins bring blood *to* the heart; arteries carry blood *from* the heart.

In a singular system, the gas must be moved efficiently into the alveolar spaces and out again through the same passages. A dual system, comparable to the inflow and outflow blood vessels of the lung, would utilize much valuable lung space and reduces the effective gas exchange area of the lung by more than 30%. Instead, a gas "pump" is used to move the oxygen-laden gas mixture called *air* into and out of the alveolar spaces. This gas pump is actuated by the muscles of the rib cage of the chest and by the muscular, dome-shaped diaphragm that separates the chest (or thorax) from the abdomen.

During inhalation, the ribs move upward and outward while simultaneously the dome-shaped diaphragm flattens downward.

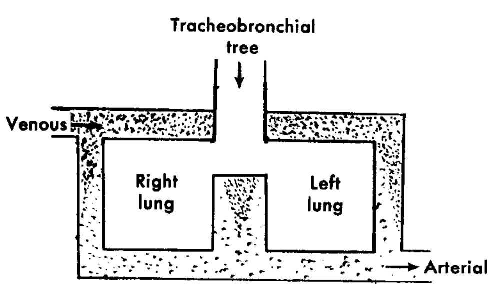

Fig. 1-1. Schematic representation of singular ventilatory system and dual blood system of lungs.

These concurrent actions enlarge the volume of the thorax, increasing its capacity from about 2 to 7 liters. Air, which is at the positive atmospheric pressure of 15 pounds per square inch (psi), rushes by way of the tracheobronchial tree into the alveolar sacs to equalize the negative pressure in the lungs. This air inflates the lungs to meet the higher capacity demanded by the thoracic expansion.

Similarly, during exhalation, the ribs move downward and inward while the diaphragm rises from its flattened position to its higher, domed shape. This, of course, decreases the volume of the chest and forces out the "used" air. The pressure in the chest is obviously higher during exhalation than that of the atmosphere.

Atmospheric air is relatively dry, and, if allowed to contact the sensitive tissues in the lungs (such as the delicate alveolar membranes), it would dry them and cause injury. Incoming air is humidified by the mucous membranes in the nasal passages and saliva in the mouth. The air is also warmed to keep it from chilling the lungs. Similarly, the surfaces over which inspired air passes may also serve to cool air that is somewhat warmer than body temperature to prevent overheating of the lung.

To supply enough oxygen for exchange in the lung, how much air is involved? When the lungs are fully expanded, they will hold from 6 to 7 liters of air. This is termed the *total capacity.* When a complete exhalation is made and as much air as possible has been forced out, there is a little more than a liter of air left in the lungs. This capacity is called the *residual volume.* The *functional residual capacity* is the amount of air, a little more than 2 liters at rest, left in the lungs after a normal exhalation.

The functional residual capacity is the quantity of air that actually reaches the alveolar spaces. An adult human at rest inhales and exhales about a 0.5 liter of air with each breath. This 0.5 liter, under ideal conditions, replenishes the 2-liter supply—the functional residual capacity—with an amount of oxygen equal to that absorbed by the venous blood passing through the capillaries. Similarly, an amount of carbon dioxide is removed by each breath equal to the amount given up to the lung by the blood for removal.

At rest, one may breathe from ten to fourteen times a minute, an exchange of 5 to 7 liters of air per minute. During intensely vigorous exercise, this may increase to 80 to 120 liters per minute (L/min). It must be remembered that only the fresh air that reaches the alveoli and mixes with the functional residual capacity is utilized. There is little or no exchange of gases in the bronchi and their many subdivisions. This volume, along with that of the trachea, is called *dead space,* since the air contained therein is not utilized. The 150 cubic centimeters (cc) of dead space account for an unusable volume of 2 to 2.5 L/min at rest.

If it is important to supply sufficient oxygen-laden fresh air to the alveoli, it is likewise important to supply the proper amount of carbon dioxide–laden venous blood to the alveolar capillaries. Just as the gas mixture (air) begins its travels in a single tube, the blood begins by being ejected from the right ventricle of the heart into the main pulmonary artery. This vessel divides first into the right and left pulmonary arteries, then into an increasingly greater number of branches and subbranches. The branches ultimately form hundreds of millions of short, narrow, thin-walled capillaries. An alveolar capillary is just wide enough to allow one red cell to pass through at a time, about 5 to 10 μ in diameter. The capillary wall is less than 0.1 μ thick while each capillary may range in length from 0.1 to 0.5 millimeter (mm).

Because of the many branches and the short length of the capillary network, the force of the right ventricle necessary to drive 5 to 10 liters of blood through the lungs need only be a pressure equal to about 10 millimeters of mercury (mm Hg). It only requires a slight increase in this driving pressure to push through a maximal flow of 30 liters of blood per minute. However, in spite of this vast network of blood vessels, the volume of blood in the lungs at any given moment will be only 70 to 100 ml.

At rest, a single red cell may stay in the capillary for about ³/₄ second. During vigorous exercise, that trip may take no more than ¹/₃ second, still long enough for oxygen transfer. At rest the lungs may transfer only 200 to 250 ml of oxygen, but during strenuous exercise, this can grow to 5.5 L/min. Blood ordinarily will absorb 1.34 ml of oxygen per gram of hemoglobin. A person at rest with a normal amount of hemoglobin in the red cells need only have the heart pump about 5.5 liters of blood per minute to allow the tissues to extract 20% to 25% of the total amount of oxygen carried by the red blood cells.

Efficiency in the lung means having the necessary volume of blood exposed to the right amount of oxygen for the proper length of time. If for some reason a less than adequate supply of air is available, the