Textbook of Disorders and Injuries of the Musculoskeletal System

ROBERT B. SALTER

AN INTRODUCTION TO ORTHOPAEDICS, RHEUMATOLOGY, METABOLIC BONE DISEASE, REHABILITATION AND FRACTURES

the Musculoskeletal System

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Foreword

Medical education, with its traditional three-fold commitment to patient care, research, and continuing education, presents a difficult challenge. The complexity of medical education requires a new set of values to be placed upon the selection of subjects which are considered essential for all physicians. The term "core curriculum" has been used widely, but seldom has it been defined. It would now appear that the problems in definition and implementation have come from an awkwardness in selecting and integrating the essential information into an appropriate and effective method of study of the various body systems, their physiology and pathology, and the overall impact of their disorders upon the patient as a unit in society. A doctrinaire or discipline-oriented experience for the student falls short of the objective if emphasis is upon the discipline rather than the subject material. It is with the prospect of solving these problems that Dr. Salter's new textbook on the musculoskeletal system has been written.

Medical students, for whom this book is created, have come to their schools superbly endowed with intellect, a proven capability of assimilating large amounts of information, and a willingness to serve mankind. Today's student expects his institution and its teachers to provide a basis for study and experience, and he understands that he must continue to study to keep up with new developments. While there are no simple answers to the problems of medical education, there is no question that an excellent medical textbook remains one of the essentials required by the student.

A good medical textbook provides not only information but also a philosophy or approach which makes the knowledge relevant. Ask the student and he will tell you that he is not interested in brief handbooks which summarize the favorite prejudices of a traditional discipline. He shuns the textbook which fails to provide a link between the body of scientific information and the bedside of the patient. The task of producing a new and forceful text for medical students in these times is formidable indeed. The author must have experience, ability, empathy, and dedication to the mission of teaching. He should be scientifically accurate and capable of projecting his personalized approach.

An exciting example of the new approach in medical textbook writing is Dr. Robert Salter's *Disorders and Injuries of the Musculoskeletal System*. In a superbly organized manner a vast amount of information is presented on the basic nature of the musculoskeletal system as well as on its disorders and injuries from infancy through old age. The biologic and physiologic relationships are fully developed and presented in a pattern which makes for coherence; the illustrations are both abundant and clear. The interesting and graphic manner of presentation, a native gift possessed by the author, comes through in clear style. Throughout, there shines through the scientific and clinical details a wholesome reassertion of the human element in medicine, an essence which ranks in importance with the most elegant molecular concept.

This book may mark a turning point in textbook writing for clinical subjects, and we would hope that other areas of medical education may follow with the production of books which will be equally effective in meeting the needs of medical students today. Although the text is addressed to medical students specifically, there is little question that it will be studied extensively by residents and their teachers. It may also prove to be of great value in the education of paramedical personnel who will be involved in the care of patients with disabilities of the musculoskeletal system.

Dr. Salter is respected throughout the world as one of the leaders in medical education and as a major contributor to Orthopaedic Surgery. He has been recognized internationally for his fundamental scientific investigations of musculoskeletal disorders and injuries in his laboratories, and he has advanced the orthopaedic care of children through the development of new and imaginative methods of treatment. He is an exemplary physician, and his patients as well as his students have come from all continents. His ability to inspire students whatever their age or setting, has become legendary. It was natural that many of his colleagues urged him to undertake the production of this book. The writing of the text, which is his work alone, has been carried on with the same attention to detail that has distinguished all his scientific efforts.

I join Dr. Salter's host of admiring colleagues in expressing appreciation for a service to patients through tomorrow's physicians—a task in which he has no peer.

J. William Hillman, M.D.,
Professor of Orthopaedic Surgery,
Vanderbilt University,
Nashville, Tennessee.

DEDICATION

To You—
a Medical Student of the present, a Medical Doctor of the future—
this textbook is cheerfully and respectfully dedicated

An Open Letter to a Medical Student

I have written this textbook expressly for a select group of readers, namely, *you and your fellow medical students*. A textbook that is written to meet the combined and varied needs of medical students, surgical residents, general practitioners and specialists frequently fails to meet the specific needs of each group, and in particular, the specific needs of the medical student. By writing this textbook solely for *you*, I have endeavored to fulfil *your* specific needs as a medical student in relation to the tremendously exciting and fascinating subject of clinical disorders and injuries of the musculoskeletal system.

Your specific needs as a medical student, in relation to the musculoskeletal system are to acquire the following: First, a general knowledge of the normal and abnormal reactions of the various tissues of the musculoskeletal system in order that you may come to *understand* the clinical manifestations and natural course of the more common conditions; second, a knowledge of eliciting and correlating clinical information including the pertinent history, physical signs, radiographic features and laboratory data in order that you may *recognize* the various clinical conditions when you encounter them in patients; third, a knowledge—in a general way at least—of the principles and methods of *treatment* of the more common clinical conditions.

An explanation of the title of this book may help to clarify its purpose and its scope. It is generally understood among teachers and publishers that a "Textbook" is a book written for undergraduate students. A "Textbook" as defined by Webster is "*a book containing the principles of a subject, used as a basis for instruction*". A Textbook is, therefore, quite different from a Reference Book which must be encyclopaedic in nature; it is different from a Monograph which must include virtually all available knowledge in a very limited field; it is different from an Atlas of Operative Technique; it is even different from a Synopsis, an Outline, a Manual or a Handbook. Thus, a Textbook, as suggested by its definition, should serve as the broad base and framework upon which you may build the additional knowledge that you will gain from your own clinical teachers as well as from the patients whom you will be privileged to see in the out-patient clinics and on the wards of your own teaching hospitals.

As medical students, and also as practitioners of medicine, you should think of clinical problems in your patients in relation to the *major systems* of the human body rather than in relation to the various medical or surgical specialties. For this reason I have chosen the title "Disorders and Injuries of the Musculoskeletal System" and have included a review of the preclinical sciences pertaining to the musculoskeletal system as a background for your *understanding* of the clinical conditions—both "medical" and "surgical". Thus, the scope of this textbook embodies the "medical" subjects of rheumatology, metabolic bone disease and rehabilitation as well as the "surgical" subjects of orthopaedics and fractures.

In the subtitle you will notice that I have referred to this textbook as an *Introduction* (intro—into; ducere—to lead). Indeed, this is exactly what I have tried to do—to *lead* you *into* the subject material. A good teacher is a leader to his students—one who *leads* them *into* a way of knowledge and *into* a way of thinking. While the teacher of medical students carries the heavy responsibility of *teaching*, the responsibility of *active learning* rests with *you*—the medical student. I urge you therefore to accept the responsibility of active learning, not only from this textbook but also from your own clinical teachers and from the observation of your own patients in order that you may be better prepared to serve the needs of patients who will seek your advice in the years to come. As Amiel has written "The highest function of the teacher is not so much in imparting knowledge as in stimulating the pupil in its love and pursuit".

I wish you well in your pursuit of knowledge, not only as a Medical Student of today but also as a Medical Doctor of tomorrow—and as a continuing student throughout your professional life.

Yours sincerely,

Robert B Salter

Robert B. Salter.

Acknowledgements

Every teacher is indebted to those persons, both living and dead, from whom he has learned and especially to those who have stimulated and encouraged him to teach. The teacher who undertakes to write a textbook covering a broad field such as the entire musculoskeletal system, must add to his own personal experience and knowledge the experience and knowledge of others from a variety of disciplines. He must then synthesize all of this to weave a meaningful pattern of knowledge from which students can benefit. I acknowledge with gratitude the help that many persons have given me with my task.

Two professors of orthopaedic surgery—Dr. J. William Hillman of Vanderbilt University and Dr. Albert B. Ferguson, Jr. of the University of Pittsburgh—advised the Williams and Wilkins Company that I be invited to write this textbook. I appreciate their confidence. I also appreciate Dr. Hillman's contribution of the foreword.

Many friends and colleagues, not only in North America but also abroad, have read specific sections of the manuscript during its preparation and have offered constructive criticisms. Though these persons be numerous (but not "too numerous to mention") I wish to record their names with grateful thanks.

Those whose discipline is other than orthopaedic surgery include the following: Professor David Allbrook (anatomy), Dr. James Boone (rheumatology), Dr. Patrick Conen (pathology), Professor John Darte (oncology), Dr. John Digby (rheumatology), Dr. Donald Fraser (metabolic bone disease), Dr. Bruce Hendrick (neurosurgery), Dr. Harold Hoffman (neurosurgery), Dr. Peter McClure (hematology), Dr. Gordon Murphy (neurology), Dr. Bernard Reilly (radiology), Dr. John Relton (anesthesiology), Dr. Allan Smith (family practice), Dr. Margaret Thompson (genetics) and Dr. Edward Yendt (metabolic bone disease).

Toronto orthopaedic colleagues who have so helped include Drs. Walter Bobechko, Donald Gibson, John Hall, Robert Harris, Ian Macnab and Mercer Rang. Orthopaedic colleagues from other parts of the world include Dr. William Hillman (Nashville), Professor Arthur Hodgson (Hong Kong), Professor J. I. P. James (Edinburgh), Dr. Ross Nicholson (Auckland) and Dr. Peter Williams (Melbourne). To each and all of these friends and colleagues I am especially grateful. In addition, Dr. Walter Zingg, Chief of the Division of Surgical Research in The Hospital for Sick Children, obligingly read every chapter as it was prepared and I am greatly indebted to him for his sagacious advice.

The onerous task of collecting material for over 1300 individual illustrations has been lightened by the generous help of Dr. Ted Dewar, Professor Brian Holmes, Mr. Harold Layne, Dr. Bernard Reilly and Mr. Arthur Smialowski. The job of printing and reprinting such a large number of illustrations has been cheerfully accomplished by the following members of the Department of Visual Education in The Hospital for Sick Children under the direction of Mr. Alex Wright: Mr. William Bryson, Mr. Tom Curtis, Mr. Barry Flint, Mrs. Sharon Lawrence and Mrs. Eva Struthers. To all of these persons I express my sincere thanks.

Mrs. Judith (Wunderly) Walker, a medical illustrator, has worked with me in the preparation and arrangement of the illustrations. Mrs. Walker has painstakingly prepared the clinical photographs in such a way as to provide uncluttered uniformity in the background of the final prints. In addition she has done most of the line drawings. Her industry and ingenuity as well as her dedication to her work are much appreciated.

For the typing and retyping of the manuscript I am indebted to my secretary, Mrs. Isabel Hume, whose skill as a typist is exceeded only by her good natured willingness to work.

To the staff of the Williams and Wilkins Company in general and to Mr. Dick M. Hoover, Editor-in-Chief, in particular, I am grateful for putting my manuscript between covers and also for patience shown to a somewhat compulsive author.

In her role as an assistant editor in the Department of Medical Publications of The Hospital for Sick Children, my wife, Robbie, has carefully read each portion of the manuscript as it has been written and has made many valuable suggestions; in addition, Robbie has assisted with the time consuming task of reading page proofs as well as with the preparation of the index. More important, however, in her role as my wife and as the mother of our five children Robbie has been a constant source of inspiration. For her unselfish understanding and for her abiding love I am, and always will be, most thankful.

R. B. Salter.

Contents

1

Introduction

BRIEF HISTORICAL BACKGROUND

As a medical student in the second half of the twentieth century, you live in a tremendously exciting era! As you pursue your studies of the basic sciences and of modern clinical medicine and surgery you will come to realize how much of what you are currently learning has been developed since *you* were born. This is simply an indication of the recently accelerated acquisition of scientific knowledge. However, as Cicero has said—"Not to know what happened before one was born is to remain a child." The history of medicine and surgery deserves your attention, not only because it is fascinating and inspiring, but also because it places your present knowledge in perspective and may even stimulate original thought concerning possible developments of the future. Following graduation, if you should choose to study one particular field of medicine or surgery in depth, you should delve into the history of that particular field in order that you may avoid repeating the errors of the past.

The bones of prehistoric men provide mute testimony of disorders and injuries of the musculoskeletal system, and from the beginning, man has sought ways to alleviate the crippling conditions of his fellow man. As early as 9000 B.C., in the Paleolithic Age, superstitions were being replaced by rational thinking and man was beginning to use splints for weak limbs and broken bones. In the Neolithic Age, around 5000 B.C., man had already begun to perform crude amputations of diseased or damaged limbs. The Egyptians had developed the concept of the crutch by 2000 B.C. Greece replaced Egypt as the center of culture by the fifth century B.C. and Hippocrates, through his teaching and through his students, had become the Father of Medicine. In the second century A.D. Galen, a Greek physician who moved to Rome, became the founder of experimental investigation.

The first nineteen centuries A.D. saw slow but progressive advance of knowledge in medicine and surgery, but progress in the twentieth century, and more particularly in the past two decades, has been staggering in its rapidity. The care of patients with disorders of the musculoskeletal system has evolved through several phases in the present century. First was the "strap and buckle" phase in which various braces and other types of mechanical apparatus predominated. Next came the phase of excessive surgical operations, not all of which were based on sound surgical principles. There followed the present phase which combines critical evaluation of the results of various forms of treatment and experimental research aimed at gaining a better understanding of the physiology and pathology of the musculoskeletal system. The present phase has made the study of clinical problems of the musculoskeletal system much more attractive and meaningful. The care of patients remains an art—but the art must be based on science.

You will gain much knowledge from those who have gone before you, both recently and in the distant past, but you may be assured that there is very much more that remains to be discovered and to be understood.

THE SCOPE OF ORTHOPAEDICS

While the history of disorders and injuries of the musculoskeletal system dates back to antiquity, the specialty of orthopaedics, as a branch of medicine and surgery, is relatively young. In 1741, Nicolas Andry, then Professor of Medicine in Paris, published a book, the English translation of which is "Orthopaedia, or the Art of Preventing and Correcting Deformities in Children." He coined the term "orthopaedia" from the words "orthos" (straight, or free from deformity) and "pais" (child), and expressed the view that most deformities in adults have their origin in childhood. While the term "orthopaedics" is not entirely satisfactory, it has persisted for over two centuries and is unlikely to be replaced in your academic lifetime.

The present scope of orthopaedics has come to include all ages and is considered to consist of the art and science of the prevention, investigation, diagnosis and treatment of disorders and injuries of the musculoskeletal system by medical, surgical and physical means and, in addition, the study of musculoskeletal physiology, pathology and other related basic sciences.

CURRENT TRENDS IN CLINICAL CONDITIONS OF THE MUSCULOSKELETAL SYSTEM

Our environment is the scene of continual change and from decade to decade we see many changes in the nature and the frequency of the musculoskeletal disorders and injuries that confront us. While certain musculoskeletal conditions, such as congenital deformities and bone neoplasms, have remained with us always, others have gradually become less common; in their place have arisen new problems which must receive increasing attention. Thus if you had been a medical student in the early decades of the present century, you would have been taught much about bone and joint tuberculosis, vitamin deficiencies of bone and paralytic poliomyelitis. Today, these conditions have been largely brought under control by prevention and therefore they merit less emphasis in your teaching. Other conditions, such as acute bone and joint infections, have been partially controlled, but only by the application of intensive modern treatment at the very onset of the disease. Thus, the present emphasis in teaching of these conditions must be on early recognition, or diagnosis, of the clinical picture, and on early treatment.

Severe cerebral palsy and extensive spina bifida with their associated paralytic problems are even more common than before because some infants with these conditions, who previously died in early life, now survive and grow up with their problems. The age span of man has become progressively longer and, as a result, the various degenerative conditions, such as degenerative arthritis, are assuming greater clinical importance. Likewise, senile weakening of bone, osteoporosis, with its complication of fractures in the elderly, has become an increasingly important problem. Certain conditions, such as rheumatoid arthritis, which in previous decades were treated by medical means alone, have become partially amenable to surgical treatment. The vast increase in the numbers of automobiles combined with their increasing speed has been responsible in part for the great increase in the number and severity of musculoskeletal injuries—fractures and associated trauma—and in particular the increasing number of patients who sustain multiple serious injuries involving several major systems of the body.

It is my hope that these current trends in the changing scene of musculoskeletal disorders and injuries will be reflected in a changing emphasis of teaching in this textbook, which is written for you—a medical student of the present.

SUGGESTED ADDITIONAL READING

ANDRY, NICHOLAS: *Orthopaedia*, Volumes I and II, Facsimile Reproduction of First Edition in English, London, 1743. Philadelphia, J. B. Lippincott Co., 1961.

BICK, EDGAR M.: *Source Book of Orthopaedics*, 2nd ed., Baltimore, The Williams & Wilkins Co., 1948.

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2

Normal Structure and Function of the Musculoskeletal Tissues

Having completed the preclinical phase of your undergraduate course in medicine, you will have learned much about the embryology, anatomy, histology, biochemistry and physiology of the musculoskeletal tissues in man. This is extremely important, because in order to understand the abnormal, you must have an understanding of the normal; indeed, your knowledge of the normal will serve as a broad base upon which you can build a knowledge of the abnormal. Some of the more important aspects of this broad base will now be reviewed to refresh your memory and to prepare you for subsequent study of the abnormal clinical conditions of the musculoskeletal system.

BONES AS STRUCTURES AND BONE AS AN ORGAN

Bones as *structures* serve three functions in that (1) they provide the rigid framework for the body; (2) they serve as levers for skeletal muscles; (3) they afford protection for vulnerable viscera including brain and spinal cord, heart and lungs.

Bone as an *organ* serves two additional functions in that it (4) contains hemopoetic tissue of the myeloid type for the production of erythrocytes, granular leucocytes and platelets and (5) it is the organ of storage for calcium, phosphorus, magnesium and sodium.

Embryonic Development of Bones

In the initial stages of development, the tube shaped embryo contains three primary germ layers of cells: the *ectoderm* or covering layer, the *endoderm* or lining layer and the *mesoderm* or middle layer. From the mesoderm is derived the *mesenchyme*, a diffuse cellular tissue which is pluripotential in the sense that its undifferentiated cells are capable of differ-

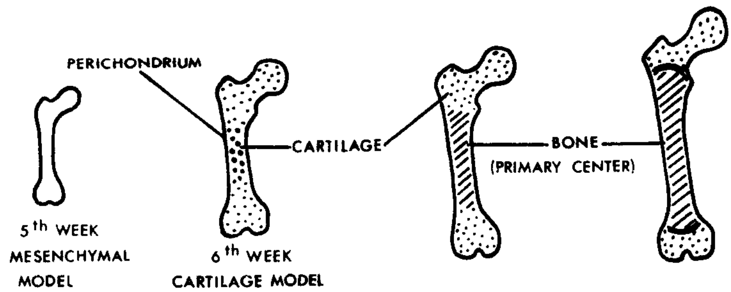

FIG. 2.1. Embryonic development of a long bone during the first six months

entiating into any one of several types of connective tissue such as bone, cartilage, ligaments, muscle, tendon and fascia. Bone and cartilage, being able to support weight, may be thought of as *supporting connective tissues*.

During the 5th week of embryonic development, the limb buds appear and in the central axis of each limb bud the mesenchymal cells become condensed in the form of a short cylinder. This cylinder is segmented by less densely cellular areas at the sites of future joints and each segment represents a tiny *mesenchymal model* of the future long bone that will develop from it (Fig. 2.1). By the 6th week, the undifferentiated mesenchymal cells of each model begin to differentiate by manufacturing cartilage matrix thereby forming a *cartilaginous model* of the future bone. The cartilaginous model grows partly from within (*interstitial growth*) and partly by the apposition of new cells on its surface (*appositional growth*) from the deeper layers of the *perichondrium* (Fig. 2.1).

After the 7th week the cartilage cells in the center of the model hypertrophy and form longitudinal rows following which the intercellular substance, or matrix, calcifies with resultant death of the cells. Vascular connective tissue then grows into the central area of dead cartilage bringing *osteoblasts* which secrete collagen and mucopolysaccharide matrix; the matrix is then impregnated with calcium salts and becomes immature bone on the calcified cartilage matrix thereby forming the *primary center of ossification*. This process of replacement of cartilage by bone is called *endochondral ossification*. The endochondral ossification advances toward each end of the cartilage model which, in turn, is continuing to grow in length at its cartilaginous ends by interstitial growth. The perichondrium by this time has become periosteum and in its deeper layer, the mesenchymal cells, which have differentiated into osteoblasts, lay down bone directly by the process of *intramembranous ossification*, there being no intermediate cartilaginous phase (Fig. 2.1).

By the 6th month resorption of the central part of the long bone results in the formation of a medullary cavity—the process of *tubulation*. At the time of birth the largest epiphysis in the body (distal femoral epiphysis) has developed a *secondary center of ossification* by the process of endochondral ossification within it (Fig. 2.2). Secondary centers of ossification appear in the other cartilaginous epiphyses at varying ages after birth. Each such center, or ossific nucleus, is separated from the metaphysis by a special plate of growing cartilage—the *epiphyseal plate*—which provides growth in length of the bone by interstitial growth of cartilage cells.

The short bones (such as the carpal bones) are developed by endochondral ossification in the same manner as the epiphyses. By contrast, the clavicle and most of the skull develop bone directly in the mesenchymal model by the process of intramembranous ossification from the periosteum without going through a cartilaginous phase.

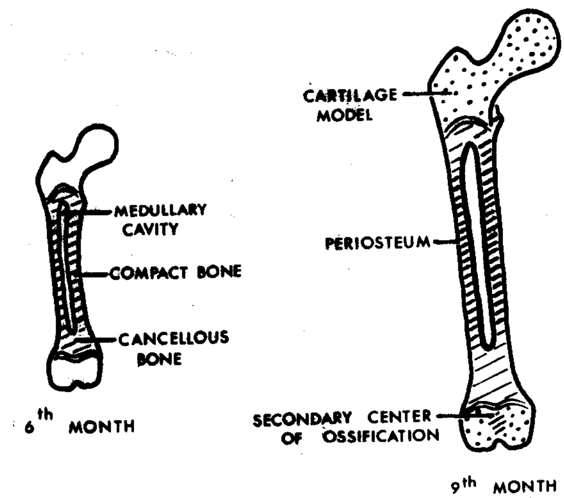

FIG. 2.2

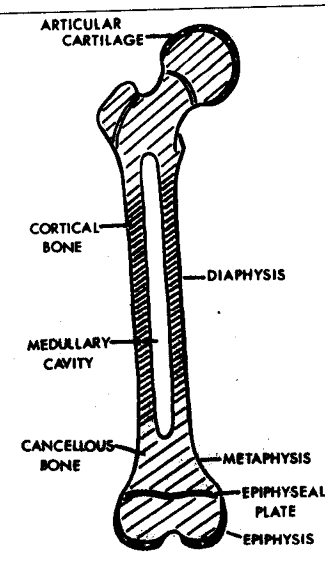

FIG. 2.3

FIG. 2.2. Development of a long bone from six to nine months
FIG. 2.3. Bone growth during childhood

During the early weeks of intrauterine , the developing embryo is particularly ceptible to noxious environmental fac- s that arrive via the placental circula- n. For example, if the mother develops ubella infection, or takes a harmful g such as thalidomide, during this crit- period, the embryonic development likely to be seriously affected. The ex- t of the resultant abnormality will pend on the *exact* phase of embryonic elopment at the time; in general, the lier the stage of development, the more ensive will be the resultant abnormal- ity. When you consider the remarkable speed and complexity of the embryonic development of the human, it is hardly surprising that some children are born with an obvious congenital abnormality; indeed, what is surprising is that the vast majority of children are completely normal at birth.

Bone Growth and Remodeling

Bones grow in *length* by one process (involving endochondral ossification) while they grow in *width* by another process (involving intramembranous ossification).

Growth in Length

Since interstitial growth within *bone* is not possible, a bone can grow in length only by the process of interstitial growth within *cartilage* followed by endochondral ossification. Thus, there are two possible sites for cartilaginous growth in a long bone—articular cartilage and epiphyseal plate cartilage (Fig. 2.3).

Articular Cartilage. In a long bone the articular cartilage is the only growth plate for growth of its *epiphysis*. In a short bone the articular cartilage provides the only growth plate for the whole bone.

Epiphyseal Plate Cartilage. The epiphyseal plate provides growth in length of the *metaphysis* and *diaphysis* of a long bone. In this site of growth a constant balance is maintained between two separate processes; (1) interstitial growth of the cartilage cells of the plate which are making it thicker, thereby moving the epiphysis farther away from the metaphysis and (2) calcification, death and replacement of cartilage on the metaphyseal surface by bone through the process of endochondral ossification.

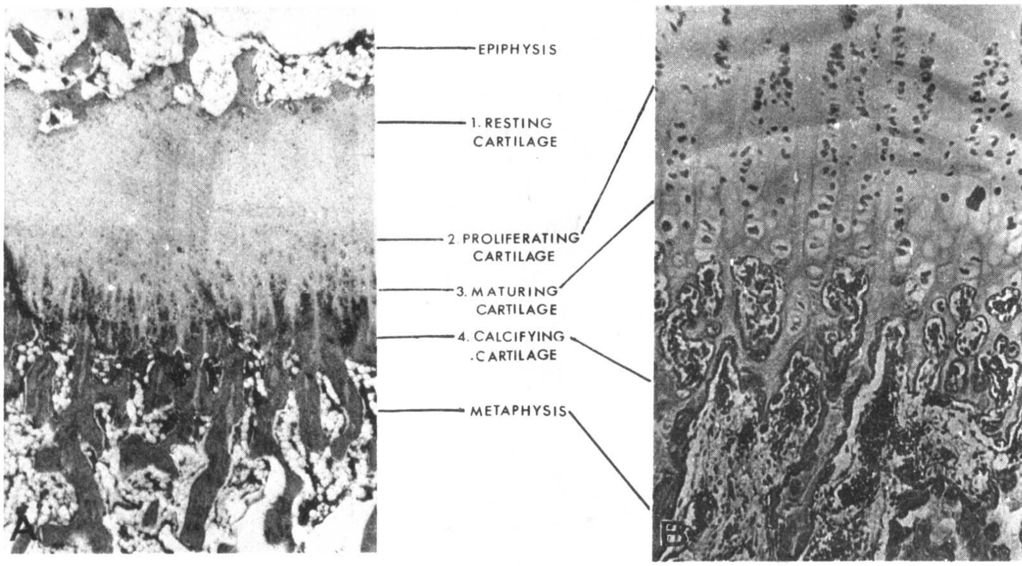

FIG. 2.4. Histology of an epiphyseal plate (from the upper end of tibia of a child). a) Low power. b) High power.

Four zones of the epiphyseal plate can be distinguished (Fig. 2.4): (1) *The zone of resting cartilage* anchors the epiphyseal plate to the epiphysis and contains immature chondrocytes, as well as delicate vessels which penetrate it from the epiphysis and which bring nourishment to the entire plate.

(2) *The zone of young proliferating cartilage* is the site of most active interstitial growth of the cartilage cells which are arranged in vertical columns.

(3) *The zone of maturing cartilage* reveals a progressive enlargement and maturation of the cartilage cells as they approach the metaphysis. These chondrocytes accumulate glycogen in their cytoplasm and produce phosphatase which may be involved in the calcification of their surrounding matrix.

(4) *The zone of calcifying cartilage* is thin and its chondrocytes have died as a result of calcification of the matrix. This is structurally the weakest zone of the epiphyseal plate. Bone deposition is very active on the metaphyseal side of this zone and as new bone is added to the calcified cores of cartilage matrix, the metaphysis becomes correspondingly longer.

Growth in Width

Bones grow in width by means of appositional growth from the osteoblasts in the deeper layers of the *periosteum*, the process being one of intramembranous ossification. Simultaneously, the medullary cavity becomes larger by osteoclastic resorption of bone on the inner surface of the cortex which is lined by endosteum.

Remodeling of Bone

During longitudinal growth of bone, the flared metaphyseal regions of bone must be continually remodeled as the epiphysis moves progressively farther away from the shaft. This is accomplished by simultaneous osteoblastic deposition of bone on one surface and osteoclastic resorption on the opposite surface.

However, remodeling of bone continues throughout life since some haversian systems, or osteons, are being eroded continually through cell death as well as through factors that demand removal of calcium from bone; therefore, deposition of bone must also continue in order to maintain *bone balance*. During the growing years, bone deposition exceeds bone resorption and the child is in a state of *positive* bone balance. By contrast, in old age, bone deposition cannot keep pace with bone resorption and the elderly person is in a state of *negative* bone balance.

Remodeling of bone also occurs in response to physical stresses—or to the lack of them—in that bone is deposited in sites subjected to stress and is resorbed from sites where there is little stress. This phenomenon is generally referred to as *Wolff's Law*, and is exemplified by marked cortical thickening on the concave side of a curved bone (Fig. 2.5) as well as by the alignment of trabecular systems along the lines of weight-bearing stress in the internal architecture of the upper end of the femur (Fig. 2.6).

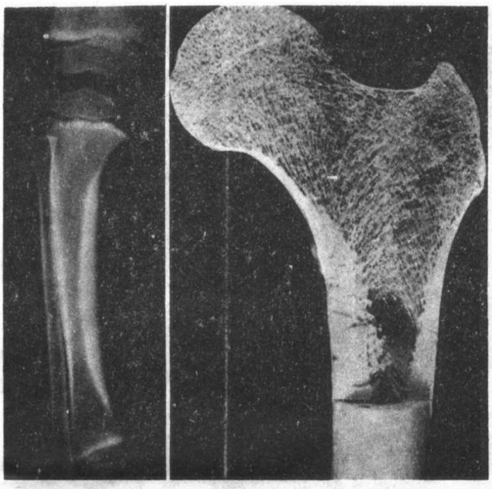

FIG. 2.5 (*left*). An example of Wolff's Law is seen in the tibia of a 2-year-old child with a bow leg deformity. Note the marked thickening of the medial cortex which is on the concave side of the deformity and which is subjected to the most stress on weight bearing.

FIG. 2.6 (*right*) An example of Wolff's Law is seen in the internal architecture of this dried specimen of the upper end of a femur of an adult. Note the alignment of the trabecular systems of cancellous bone along the lines of weight bearing stresses.

Anatomy and Histology of Bones as Structures

Anatomical Structure

Bones, from the viewpoint of their gross structure, are classified as (1) long bones (e.g. femur), (2) short bones (e.g. carpal bones) and (3) flat bones (e.g. scapula). Furthermore, each bone consists of dense cortical bone (*compacta*) on the outside and a sponge-like arrangement of trabecular bone (*spongiosa*) on the inside. In children the covering periosteum is thick, loosely attached to the cortex and produces new bone readily; in adults, by contrast, the periosteum becomes progressively thinner, more adherent to the cortex and produces new bone less readily. This fundamental difference explains, in part, why fractures heal more rapidly in young children than in adults.

Histological Structure

From the viewpoint of its microscopic structure, bone is classified in the following way (the commonly used synonyms are included in brackets):

(1) *Immature bone* (non-lamellar bone, woven bone, fiber bone).

(2) *Mature bone* (lamellar bone). (a). Cortical bone (dense bone, compacta). (b). Cancellous bone (trabecular bone, spongiosa).

The two major histological types of bone demonstrate significant differences in their relative content of cells, collagen and mucopolysaccharides.

Immature Bone. The first bone that is formed by endochondral ossification during embryonic development is of the immature type; subsequently, it is gradually replaced by mature bone so that by the age of one year, immature bone is no longer seen under normal conditions. Nevertheless, throughout life, under any abnormal condition in which new bone is formed rapidly (such as in the healing of a fracture), the *first* bone that is formed is of the immature type. Here again, the rapidly formed immature bone is subsequently replaced by mature bone.

Immature bone, also called fiber bone, or woven bone, because of its large proportion of irregularly "woven" collagen fibers, is very cellular and contains less

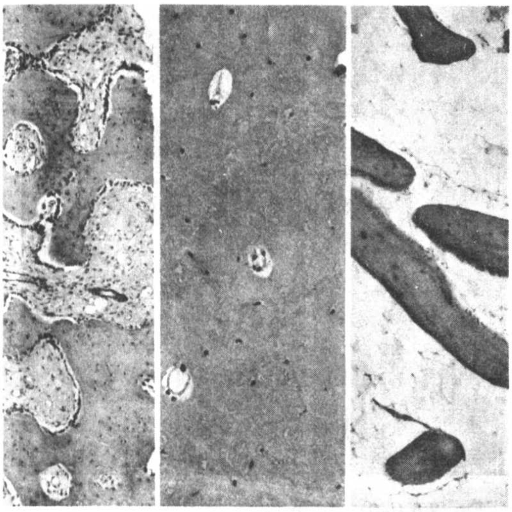

FIG. 2.7 (*left*). Immature bone (fiber bone, woven bone) in the human. This very cellular type of bone is laid down in an irregular, "woven" pattern.

FIG. 2.8 (*middle*). Cross section of the dense cortex of mature bone in the human. Note the concentric arrangement of the layers, or lamellae, around a central vessel thereby forming haversian systems, or osteons.

FIG. 2.9 (*right*). Trabeculae of mature cancellous bone in the human. The thin trabeculae are nourished by surrounding vessels in the marrow spaces.

cement substance as well as less mineral than mature bone (Fig. 2.7).

Mature Bone. In the dense cortex, mature bone is characterized by the concentric arrangement of its microscopic layers or lamellae and also by the complex formation of *haversian systems* or *osteons* which are well designed to permit circulation of blood within the thick mass of cortical bone (Fig. 2.8). As in the structure of plywood, the collagen fibrils in any given concentric layer of an haversian system course in a different direction from those of adjoining layers—an arrangement which adds strength to bone.

In cancellous bone the arrangement of lamellae is somewhat less complex because the trabeculae are thin and can therefore be nourished by surrounding vessels in the marrow spaces (Fig. 2.9).

Mature bone is less cellular and contains more cement substance as well as more mineral than immature bone.

Bone Cells and Their Function. The *osteoblasts*, which represent one type of differentiated mesenchymal cell, are essential for the process of *osteogenesis* or *ossification*, since they alone can produce the organic intercellular substance, or *matrix*, in which *calcification* can occur later. The uncalcified tissue, because of its microscopic similarity to bone (in decalcified preparations), is called *osteoid*; once calcification occurs in the matrix, the tissue is *bone*. Thus, you will appreciate that ossification and calcification are not synonymous. As soon as an osteoblast has surrounded itself by organic intercellular substance, it lies in a *lacuna* and is henceforth known as an *osteocyte*.

The large, multinucleated cells which lie on the naked or uncovered bone surfaces and which are capable of resorbing or removing bone are called *osteoclasts*. Ham believes that osteoclasts are derived from the fusion of many stem cells or osteogenic cells that cover or line bone surfaces and that the osteoclasts are, in effect, a type of foreign body giant cell. Calcium can be removed from bone only by osteoclastic activity (*osteoclasis*), which removes the organic matrix and the calcium simultaneously, a process that is more accurately described as *deossification* than as "decalcification".

Biochemistry and Physiology of Bone as an Organ

While the *gross appearance* of bones as structures changes only slowly, particularly after the period of skeletal growth, there is much *microscopic change* taking place within the bones as a result of the very active physiology of bone as an organ. The main biochemical function of bone concerns calcium and phosphorus metabolism.

Biochemistry of Bone

The biochemical composition of bone is as follows:

Organic Substances	35%
Inorganic Substances	45%
Water	20%

Organic Substances. The organic component of bone includes the bone cells as