ANATOMY FOR SURGEONS: VOLUME 3

The Back and Limbs

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PREFACE TO VOLUME 3

In *Anatomy for Surgeons* I have attempted to present in readable form that regional anatomy which is of particular importance to the surgeon. It was thus not intended that this should be a complete descriptive anatomy; rather, my attempt has been to describe and interpret, with a minimal soporific effect, the anatomical facts and concepts which the surgeon has found useful.

It has been my good fortune to have taught anatomy to medical students and others, at Duke University School of Medicine, from 1930 to 1947, and since that time to have been engaged as consultant in anatomy to the more than 600 physicians of the Mayo Clinic and Mayo Foundation, and as a teacher of exclusively graduate courses to Fellows of the Mayo Foundation specializing in the various branches of surgery. This book is a direct outcome of that experience, for it represents an expansion of the material which I present in my several courses. In addition I have been exceedingly fortunate in receiving the aid of a number of specialists, my friends and colleagues of the Mayo Foundation and Mayo Clinic, in the preparation of this work. Every chapter has been read and criticized by one or more surgeons whose operating schedules keep them in constant touch with the particular anatomy described in that chapter. The *modus operandi* of this has been as follows: After I had completed and revised a chapter, a copy of the manuscript was given to a surgeon or specialist particularly interested in all or a part of the chapter, with a request for criticism as to content and its applicability to the surgery of that area. Suggested changes, deletions, and additions were written directly upon the manuscript, which was returned to me. I incorporated them into the final text, often consulting again with the surgeon before so doing, and in some cases obtaining additional criticism after rewriting a part. It is a pleasure to acknowledge my debt to these men, who are listed on the preceding pages. It should be obvious, however, that they are in no way responsible for errors in facts, concepts, or phraseology, since I, as the author, solely bear the blame for these.

Our courses for Fellows involve not just discussions of the rationale of various operations in which these young surgeons are interested—that is just the dessert, so to speak—but also detailed expositions of the basic anatomy of the field in which they are interested. In my experience, it is very fundamental anatomy, especially that not so easily seen at the operating table, which must form the *pièce de résistance* of any graduate course in anatomy. With knowledge of or access to these fundamental details, the young surgeon has a firm foundation upon which to build his own clinical experience.

In preparing this text, I have, then, had two goals: first, to present to the younger surgeon not only a review of the broad basic anatomy with which the surgeon is necessarily concerned, but also a discussion of those details upon which the more mature surgeon, consciously or unconsciously, bases his daily work; second, to provide for the more mature surgeon both a refresher for those details which are, perhaps, slightly outside his own special field of interest, and a source of ready reference to the details which, although lying in his own field, he cannot expect to keep constantly in mind. To attain these goals, the text is so organized that any chapter can be read through as a whole, or that specific parts of a chapter can be consulted for discussions of particular points. To make the discussions of the various subjects complete in themselves, a certain amount of repetition is necessary; it is hoped that undue repetition has been avoided by the use of abundant cross references.

The book has been divided into three volumes: "The Head and Neck"; "The Thorax, Abdomen, and Pelvis"; and "The Back and Limbs." This subdivision was intended to serve two purposes: to prevent an individual volume from assuming such proportions that it could not be readily packed or carried, or even read comfortably in bed if one has that habit; and to allow the surgeon interested in only one field, for instance the head and neck, to have the pertinent volume on his reference shelf if he so desires, without including a large mass of material on other parts of the body in which he has no interest. The last two volumes of this series have grown beyond the size originally envisioned for them, largely nullifying the first of these two worthy purposes.

No attempt has been made in the present work to describe the indications for or the detailed technic of specific operations, for these are matters that belong to surgery and not to anatomy. Nevertheless, certain anatomical facts and concepts are of importance only as they pertain to surgery, and most surgical procedures are based upon the anatomy, or the physiological anatomy, of the part concerned; an example of this is the detailed anatomy of the extensor apparatus on the fingers, understanding of which has made possible more satisfactory restoration of function to a hand crippled by lesions of the extensor tendon or its adjuncts.

Throughout the book, reference is made to specific surgical procedures. Some of them will undoubtedly not stand the test of time, and will be superseded by others, based upon different concepts, refined technics, or newer knowledge, but—and this is worth emphasizing—the basic anatomy will remain the same, even though it may be regarded from an entirely new and different angle. In a similar fashion, if the text is to be both accurate and understandable, experimental work bearing upon various questions must be referred to, and at times the embryology underlying a certain condition must be understood. Every attempt has been made, therefore, to gather together pertinent material from all available sources.

Since no one can of his own knowledge possibly vouch for the numerous supposed facts presented in such a book as this, I have endeavored to supply appropriate references to the original literature. No pretense is made that the literature on any subject is exhaustively covered. Rather, I have selected references which have seemed to me to contribute something to the anatomy under discussion, and have proved useful to me in my teaching. When a number of articles upon the same subject have met these criteria, those actually cited have been chosen because they were relatively recent articles, because they presented new or opposing viewpoints or confirmed perhaps debatable concepts, or afforded a good review of the question as a whole. No question of priority, or even of superiority, is therefore implied in this selection. As will be noted, the references are almost without exception to literature written in English.

I would have real objections to the classification of this book as a "practical" or "surgical" anatomy, although it is intended to be directly useful to the surgeon. The terms are misleading: the former implies a sharp differentiation between that anatomy which is practical and that which is impractical from the standpoint of a clinician, while in reality any such attempted differentiation is necessarily ill-defined and subject to constant change, as exemplified by the fact that details and concepts of anatomy which were of no interest to the surgeon even ten years ago have become, through advances in technic, essential information; the latter term implies that there is some mysterious difference between plain or ordinary anatomy and surgical anatomy, whereas the difference really is only one of emphasis, and of point of view, concerning the same anatomical facts.

Many of the illustrations are purely diagrammatic, and are planned to accompany the text in much the same manner that one draws diagrams upon the blackboard to illustrate points in a lecture. They are therefore intended to be simple and easily comprehended. For more complete depiction of various regions, and accurate representation of individual anatomical specimens, there are available a number of excellent atlases, of which the surgeon presumably owns at least one. Some of the illustrations in this text are original, so far as the author is aware; others are diagrams, or variations of them, that have been the common property of anatomists for years; still others are simplifications or modifications of more elaborate illustrations appearing in texts or the original literature; and for this volume I have been able to borrow extensively from original figures appearing in other works. The source of the original drawing, whether borrowed directly or modified, is acknowledged in the accompanying legend; I am indebted to the various authors and publishers for their permissions to use these drawings. Except where a drawing has been directly reproduced, the general procedure has been that I sketched, as accurately as possible, the figure desired, whether it was an original or a redrawing or adaptation from another figure; this sketch was then turned over to the artist (Miss Aileen Young for the majority, Mr. Vincent P. Destro for the others); my own pencil sketch was then converted by the artist, with Mr. Russell Drake's supervision, into a finished pen and ink drawing. The results, while often intentionally diagrammatic, much surpass my own skill, and I would be ungrateful indeed if I did not acknowledge my indebtedness to the patience, ability, and understanding of these medical illustrators. The halftones drawn for this volume are entirely the work of Miss Young and Mr. Destro.

In the earlier volumes of this series, note was made of the confusion in anatomical terminology arising from certain inadequacies in the B.N.A. and from the fact that various countries had their own modernizations of the B.N.A. That problem seems now to be solved for the most part, since the major countries (including all the English-speaking ones) have finally agreed upon a terminology that, with subsequent revisions as necessary, is expected to be followed internationally from now on. It was also agreed that the strictly Latin form, sometimes so ponderous, could be modified to accord more with the vernacular of the various countries.

This "new" terminology, the Nomina Anatomica or N.A., necessarily represents a compromise among groups with varying views as to what is the best terminology, but actually departs relatively little from the terminology that most of us are accustomed to, whether it be the original B.N.A., the B.R., or some other variant; changes from the B.N.A. are, for the most part, to terms that are more accurate or more clearly descriptive, and therefore the new terms are largely self-explanatory.

Because of its obvious advantages, I have attempted to use the N.A., in Latin or English, throughout this volume; any lapses from it are inadvertent, the result of old habits that are not easily changed. As in the previous volumes, however, I have tried to include more commonly used synonyms at least once. On occasion, where a new term may seem particularly strange, I have even used a better-known synonym repeatedly; this is purely, of course, to insure ready understanding, for it is to be hoped that now-obsolete terms will not be perpetuated, and that future generations will find themselves free of the cumbrous synonyms with which most of us have necessarily cluttered our memories.

In addition to the reading by established surgeons and others referred to previously, various parts of the text have also been read by several Fellows of the Mayo Foundation. I am grateful to them for their suggestions. For the present volume these men include Drs. H. G. Kroll, L. F. A. Peterson, R. L. Phifer, and J. J. Sanchez.

Finally, I must also acknowledge my gratitude to the several people who have especially helped in the mechanics of the preparation of this book. These include, in addition to the medical illustrators, Dr. Carl Gambill, of the Section of Publications, who has carefully gone over the manuscript for me and given freely of his advice and experience; the publishers, who have been liberal with their enthusiasm for this, to me, formidable project, and who have given me every aid; and last, but by no means least, my secretary, Miss Esther Peters.

W. HENRY HOLLINSHEAD

Rochester, Minnesota

CONTENTS

CHAPTER 1

Some General Considerations

SINCE this volume deals largely with bones, muscles, nerves, and blood vessels, and there are a number of general facts and principles that are equally applicable to these structures in whatever region they occur, it seems appropriate to consider some of these.

BONE, CARTILAGE, AND JOINTS

BONE

Bone regularly occurs in two forms, compact and spongy (cancellous). Compact bone forms the surface of all bones, and the major part of the shaft of long bones; spongy bone occupies the ends of long bones, and permeates the bodies of the short and flat bones. The large medullary cavity in the shaft of a typical long bone is, in the adult, occupied by yellow marrow. The much subdivided medullary cavity in spongy bone is occupied by red marrow, which produces the granular leukocytes and the red blood cells.

Compact or cortical bone contains the Haversian canals, longitudinally running channels for the accommodation of blood vessels, about which the bone is laid down in concentric lamellae; spongy bone also consists of lamellae, but these are in flat branching plates rather than concentric circles. Koch regarded spongy and compact bone as being identical in their physical properties, weight for weight.

The articular surfaces of bones are covered, outside the thin plate of cortical bone, by hyaline cartilage. The remainder of the bone is covered externally by the periosteum, a layer of specialized connective tissue that is firmly bound to the bone by some of its fibers, which enter the bone as Sharpey's fibers, and that also gives off blood vessels into the bone. The outer layer of the periosteum is denser, and contains the periosteal blood vessels, while the inner layer is looser and contains in adults the fibroblasts which can, under the proper conditions, proliferate and form osteoblasts for the reconstruction of cortical bone. The endosteum is a thinner layer of connective tissue lining the bone where it abuts on the marrow cavity; it also contains cells which are capable of forming bone (p. 11).

TRABECULAR STRUCTURE AND MECHANICS

The structure and the mechanical properties of bone have been the subject of numerous investigations. "Wolff's law" states essentially that every bone is constructed in such a fashion as to allow it to resist the forces applied to it, so that if the direction of the forces change, there will be a corresponding change in the structure of the bone. Koch's analysis of the compressive and tensile stresses in the femur, by mathematical means, led him to conclude that this rather complex bone accords strictly in structure to the best engineering principles—maximal strength with a minimal use of material. Comparing the calculated lines of tension from being pulled apart—while the trabeculae arising from the medial side of the femur and arching upward and laterally correspond to the lines of compressive stress—that is, resist the compressive forces brought about by a load on the head of the femur. Similarly, Koch showed that the absence of trabeculae in most of the shaft is also ac-

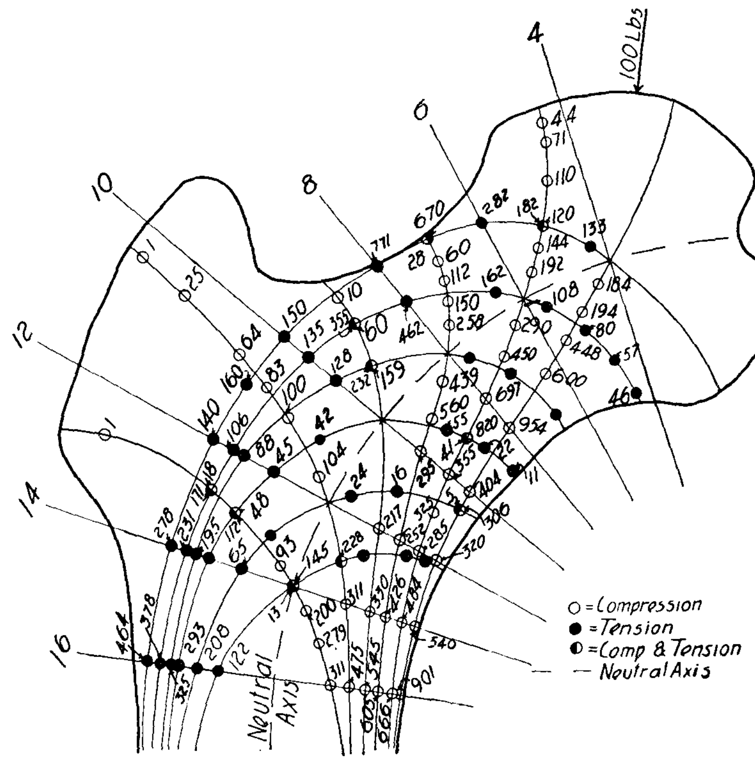

Fig. 1. Koch's calculations of the maximal tensile and compressive stresses in the upper end of the femur when there is a load of 100 pounds on the femoral head. The numbered lines extending across the femur represent the levels of the cross sections that he studied for the bony architecture. (From original of Fig. 19*a,* Koch, J. C.: *Am. J. Anat. 21:*177, 1917.)

and compression in the head and neck of the femur (Fig. 1) with the actual arrangement of the trabeculae here (Fig. 2), he apparently showed that the trabeculae are arranged in exactly the pattern demanded by his mathematical analysis.

In general, the trabeculae arising from the lateral side of the femur and arching medially correspond to the calculated tensile stresses—that is, the internal force in the bone that tends to keep two adjacent planes cording to mathematical and engineering principles (for the stresses borne by this part are most economically cared for by a tube such as is offered by the cortical bone here), and that the trabeculae in the lower part of the femur are arranged in accordance with the stresses here. While it has been objected that mathematical analyses, based as they are on the behavior of metals, do not necessarily reveal the true condition obtaining in bone, the relatively recent studies of

Evans and his co-workers (for instance, Evans and Lissner) on deformation and fracture of the femur under actual conditions of load seem to have agreed in general with Koch's analysis.

The physical properties of bone vary somewhat. Koch quoted the tensile strength—the resistance to being pulled apart—of bone along its long axis as varying from about 13,200 to about 17,700 pounds per square inch, its compressive strength—resistance to being crumbled—along its long axis as varying from about 18,000 to 24,700 pounds per square inch. These figures can be compared with a tensile strength of 65,000 pounds per square inch, a compressive one of 60,000, for medium steel; a tensile strength of 28,000 pounds, a compressive one of 42,000, for copper; a tensile strength of 1,500 pounds, a compressive one of 15,000, for granite; and a tensile strength of 12,500 pounds, a compressive one of 7,000, for white oak when the load parallels the grain, but both tensile and compressive strengths of only about 2,000 pounds per square inch when the load is at right angles to the grain. Koch pointed out that the tensile strength of bone is regularly less than its compressive

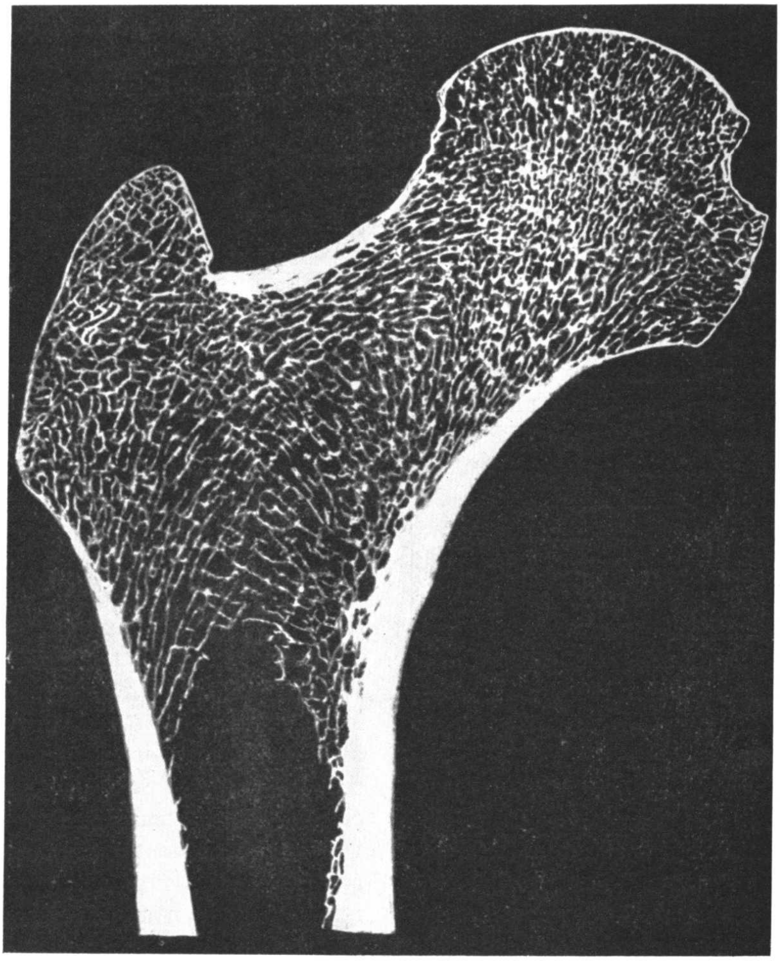

Fig. 2. A thin frontal section of the femur to show the trabecular structure. Note the correspondence between the trabeculae here and the lines of tension and compression in Figure 1. (From original of Fig. 21, Koch, J. C.: *op. cit.,* Fig. 1.)

strength, a finding which seems to be also substantiated by the observation of Evans, Pedersen, and Lissner that fractures of the femur regularly arise as a result of failure of the bone under tensile strain—which means they originate on the convexity, not the concavity, of the femur distorted by a load or a blow.

Evans and Lebow have restudied, by engineering technics, the tensile strength of bone as a whole, and found that it varies not only from bone to bone but within different parts of the same bone. Thus the middle third of the femur was found to have a greater tensile strength than the proximal and distal thirds, and the middle third of the tibia had a greater tensile strength than did the middle third of the femur. The tensile strength of wet specimens, more nearly approximating living bone, was found to be considerably less than that of dried specimens, concerning which figures are usually quoted; the average tensile strength of the middle third of wet specimens of the femur was only a little more than 12,000 pounds per square inch, while that of dried specimens exceeded 16,000 pounds. In contrast, however, wet specimens elongated under tension much farther than did dried bone—that is, were able to absorb a greater amount of energy.

CONSTITUENTS

Cortical bone contains about 25 to 30 per cent of water (Evans and Lebow). Of the dry weight about 60 to 70 per cent is mineral, apparently tiny crystals of $3Ca_3(PO_4)_2 \cdot Ca(OH)_2$ (an hydroxyapatite) with carbonate and citrate bound to their surfaces (McLean), while the fibrous connective tissue, collagen or ossein (ostein), constitutes about 30 to 40 per cent of the interstitial substance. In general, the relative amount of collagen decreases from young individuals, in whom the high content presumably leads to "green stick" fractures, to elderly individuals in whom the fibrous tissue is much reduced and the bones are therefore brittle. The loss of calcium salts as in rickets and osteomalacia is, of course, of great importance clinically.

The collagenous fibers in compact bone are usually described as being arranged in general in alternating circular and longitudinal lamellae about each Haversian canal, it being admitted that neither set of fibrillae corresponds as a rule exactly to these directions, but both are, rather, usually oblique; much of the mechanical strength of bone has been assigned to this alternating arrangement of the fibrillar system. Ruth said, however, that there are no longitudinal fibrillae at all; he described the alternating layers as consisting rather of circular fibers and radial fibers, but with both of these sets of fibers being in the transverse plane of the bone, and none in its longitudinal axis.

BLOOD AND NERVE SUPPLY

The *blood supply* to bones varies according to the shape of the bone. In long bones, however, there are generally three sets of vessels: one or more nutrient arteries, accompanied by paired veins; periosteal vessels; and vessels associated with the joint capsules, which penetrate the ends of the long bones. The nutrient artery of most long bones is of somewhat variable origin when there are two or more associated vessels that might give rise to it, and may be multiple instead of single; for instance, the committee considering the new anatomical nomenclature (N.A.) commented upon the variation in the nutrient arteries to long bones, and felt that because of this variation it was unwise to name many of them as branches of specific vessels. The concept that "the" nutrient artery is necessarily the first vessel to invade the cartilage matrix of the forming bone, and hence that the line of intersection of the nutrient canal with the center of the bone marrow indicates the original center of the bone, from which the amount of growth at either end can be calculated, is not now generally adhered to (for instance, Hendryson).

The nutrient artery or arteries, with their accompanying veins, usually penetrate the cortex obliquely (their direction, whether distal or proximal, indicating the end at which the greatest growth in length of the bone has occurred) and supply the greater part of the marrow and an inner portion of the cortical bone. The periosteal vessels, much smaller, supply the outer part of the cortex. The vessels associated with the articular capsules at the ends of the bone penetrate the fibrous capsule and turn up or down toward the end of the bone between the reflected synovia and the bone; they are both more numerous and relatively large as compared with the periosteal vessels, and are responsible for the fact that the part of a bone lying inside an articular capsule regularly shows rather large and numerous vascular foramina, whether it belongs to the epiphysis or the shaft (Harris, '29); the foramina here are multiplied by the fact that the veins emerge separately from the arteries, in contrast to the nutrient vessels of the shaft. These vessels, sometimes called metaphyseal vessels, are distributed both to the bony substance and to the marrow, and represent really both periosteal and nutrient vessels for the ends of the bones.

Through the periosteal and nutrient vessels the major part of a long bone receives its blood supply from numerous points along its length, therefore a fracture cannot deprive either part of all its blood supply; in contrast, intracapsular fracture of a bone, such as one of the neck of the femur, necessarily involves more or less interruption of the blood supply to the smaller fragment, hence osteogenesis for repair of such a fracture is typically poor. In growing bone, while the epiphyseal cartilages (plates) are still present, there is no anastomosis between the vessels supplying the epiphysis and those supplying the shaft, since the cartilage is not penetrated by blood vessels; after disappearance of the cartilage, these two sets of vessels establish continuity with each other.

Hirsch regarded the nutrient vessels as being the most important blood supply to the cortex of the shaft of the long bone, and said that the periosteal vessels have a limited capacity to serve as a source of collateral circulation; however, Huggins and Wiege interrupted the main nutrient vessels to the femur of rabbits (there are usually three chief vessels in this animal) and described the effect as being primarily a necrosis of the marrow, especially the central portion. Foster, Kelly, and Watts reported that combined interruption of the nutrient vessels and stripping of the periosteum from most of the length of the femur in rabbits produced infarction of both the bone marrow and the bone in most of the animals; this involved the entire thickness of the cortex but was largely confined to the middle third of the femur. In the rapidly growing animals upon which they worked, they found that while infarction impaired the rate of growth in the circumference of the bone, it did not impair longitudinal growth, thus indicating that the metaphyseal vessels, still intact, were capable of supplying the epiphyseal cartilages. (Kistler, also working upon the rabbit, concluded that growth in the cartilage of the epiphyseal plate is maintained by the vascular supply to the epiphysis, but that the production of bone in the growth of the shaft depends upon the circulation from the shaft.)

Coolbaugh reported that interruption of the vascular supply to bone leads during about the first 4 days to a decrease in the density and modulus of elasticity of compact bone, but that by about the fifth day the values for avascular and normal bone are about equal, and that from about the fifth or sixth day onward the avascularized bone shows an increase in density and modulus of elasticity as compared with normal bone.

Lymphatics are present in the periosteum, and have been said also to accompany blood vessels into the bone, but little seems to be known about them.

Nerve fibers also have been traced into bone, along the blood vessels. Kuntz and Richins traced nerve fibers along the blood vessels into the bone marrow, and found that for the most part they remain related to the blood vessels; through degeneration experiments, they showed that some of them were afferent and some were sympathetic.

Hurrell described nerve fibers along the blood vessels in the Haversian canals of compact bone, and said that they left the canals to penetrate the interstitial substance of the compact bone; he expressed the idea that some of these fibers are concerned with pain from bone, and that others have a trophic function. The staining and identification of nerve fibers in bone matrix is a difficult and tricky problem, and whether such fibers actually exist is perhaps questionable; certainly, pain associated with fracture or bone tumor can be explained upon the basis of stimulation of fibers along blood vessels of the marrow and perhaps the Haversian canals, and in the periosteum, without resort to endings in the bony matrix. The concept that there may be nerve fibers in the bone which have a trophic function, in some way governing the growth and repair of bone, is apparently negated by the experiments of Corbin and Hinsey and of Schiller: the former workers destroyed the sympathetic and afferent innervation to one hind limb of a number of cats, and compared the denervated and normally innervated bones and joints at periods ranging from 2 weeks to 3½ years. In the animals whose movements were restricted, no changes at all were found; in those that were allowed to run freely in large cages there was trauma of the anesthetic hip joint, but there were no other changes except those attributable to this trauma. Similarly, Schiller was able to observe no changes in the bones of a limb as a result of denervation, or even as a result of immobilization of a denervated limb.

Growth and Repair

With the possible exception of the clavicle, the ossification of which is peculiar, all the bones of the limbs and vertebral column are preformed in cartilage. Erosion of cartilage through the ingrowth of blood vessels tends to occur at about the middle of the cartilaginous mass, and bone laid down where the cartilage has been eroded establishes the first center of ossification. In the case of long bones (Fig. 3) the first center of ossification is for the shaft (diaphysis); for the various vertebrae, three primary centers appear approximately simultaneously, one (or two uniting quickly into one) for the body and two for the arch. Centers of ossification grow by a continuation of the process through which they arose, erosion of cartilage and replacement by bone; as the bony center for

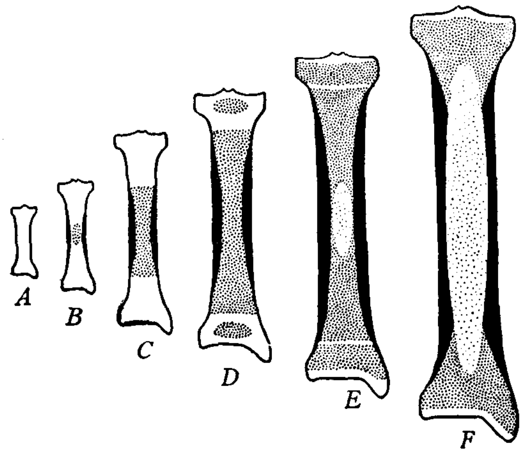

Fig. 3. Schema of the ossification and growth of a long bone. White represents cartilage; stipple, spongy (endochondral) bone; black, compact (perichondral) bone. **A** is the cartilaginous stage; in **B** and **C** both endochondral and perichondral bone appear and increase; in **D** the epiphyseal centers have appeared, in **E** the epiphyses have reached their full growth, and in **F** they have joined the shaft. In the last two stages the marrow cavity (light stipple) appears and spreads through resorption of spongy bone. (From Arey, L. B.: *Developmental Anatomy* [ed. 6]. Philadelphia, Saunders, 1954.)

the shaft of a long bone spreads it soon comes to replace the entire cartilaginous thickness of the shaft, and thereafter growth in diameter of the bone can occur only through the activity of the osteoblasts associated with the periosteum.

CENTERS OF OSSIFICATION

Each carpal bone normally ossifies entirely from a single center; so does each tarsal, except for the calcaneus, which normally develops an epiphysis at its posterior end. In the vertebrae, epiphyseal centers appear at the tips of the spinous and transverse processes. The larger long bones develop two epiphyseal centers of ossification (Fig. 3), one in each cartilaginous end of the developing bone. The shorter long bones —the metacarpals and metatarsals, and the phalanges of both the hand and foot— typically develop only single epiphyseal centers, which are in the distal ends of the second to fifth metacarpals and metatarsals, in the proximal ends of the first metacarpal and the first metatarsal, and in the proximal ends of all phalanges. Finally, additional epiphyseal centers appear in the cartilage of the ends of some long bones—for instance, centers for the several parts of the distal end of the humerus. As the epiphyseal centers expand, most of the cartilage at the ends of a long bone is also replaced, but a thin layer of cartilage remains over the articular surface of the end of the bone, and a plate of cartilage, the epiphyseal cartilage or epiphyseal plate, persists for a time—it may be years—between the ossified epiphysis and the ossified shaft.

The details of ossification of the various bones are best considered in connection with the regions in which they occur. In general, however, centers for ossification of the long bones appear during the seventh and eighth weeks of fetal life (that of the clavicle, the first to appear, is usually said to be recognizable at 5 weeks), and so do the primary centers for the vertebrae except for the coccygeal ones; by the time of birth the major part of each long bone, the shaft, is completely ossified. In contrast, the single center of ossification for most of the carpals and tarsals appears only shortly before or, more commonly, after birth, and so do the centers of ossification for the epiphyses, and for the coccygeal segments of the vertebral column; these parts, then, are entirely cartilaginous at birth or have only a small nucleus of ossification in the relatively large cartilaginous mass.

The dates of appearance of the centers of ossification of the carpals and tarsals vary markedly with the bone: for instance, a center is recognizable in the calcaneus at about the sixth month of prenatal life, and centers for all the tarsals appear during approximately the first 4 years of postnatal life, while those for some of the carpals may appear slightly later—that of the pisiform, an extreme, being usually not visible until the ninth or tenth year in females or the thirteenth to fourteenth year in males (Paterson). Similarly, the dates of first appearance of the epiphyseal centers vary even more markedly according to which one is being considered: centers for the head of the humerus, the lower end of the femur, and the upper end of the tibia are either present at birth or appear shortly thereafter; the epiphyseal center of the olecranon does not appear until about the age of 11; and the epiphyses of the vertebrae typically appear between the ages of 15 and 20.

According to Hill the appearance of ossification centers from about the second month of prenatal life onward is rather accurately correlated with the age of a healthy fetus, sufficiently so that the age may be calculated from the appearance of the centers. Hill, Noback, and Robertson; Francis and his coworkers ('39, '40); Flecker ('32, '42); Davies and Parsons; Paterson; and others, have provided extensive data upon the time of appearance of the various centers of ossification, and the time of fusion of epiphyseal centers with the shaft. Pryor ('36a and b) emphasized the bilateral symmetry of ossification in infants and children, and the fact that identical twins and triplets show similar small anomalies in ossification (of the hands), while there are no more similarities between nonidentical twins than between parents and children.

Pryor ('28) stressed the fact that the carpal bones ossify in the female sooner than they do in the male, and that earlier ossification in general is typical of the female child; Paterson found earlier ossification, not only in regard to the carpals and tarsals but also in regard to the dates of appearance of all the epiphyses and the dates of their union to the shaft, to be typical of the female. Hill noted that even during the last 3 months of prenatal life the female, as judged by the centers of ossification, matures somewhat more rapidly than does the male. In general, however, the earlier a center of ossification appears, the less likely is there to be any difference between its time of appearance in the male and the female, while the later it appears, the greater the gap between the two sexes in the time of appearance. In postnatal life, not only are the dates of appearance of the epiphyses in the female up to 6 months earlier than those of similar epiphyses in the male, but fusion of the epiphyses with the shaft also typically occurs earlier in the female than in the male; the difference is usually a year or more, and in the case of certain epiphyses may be as much as 5 years (Paterson). As a general rule, the sooner a center of ossification appears in one of the two epiphyses of a long bone, the later this epiphysis is united to the shaft.

GROWTH

Once the shaft of a long bone is ossified, as it generally is long before birth, growth in diameter of the bone necessarily involves an entirely different method, for there is no further peripheral cartilage to be replaced. Therefore, growth in diameter of a long bone is primarily periosteal, with successive layers of bone being laid down on the periphery by the periosteum, while the inner layers of bone, adjacent to the medullary cavity, are being constantly resorbed in order to enlarge the medullary cavity, and reorganized into Haversian systems around the blood vessels. According to LeBlond, Wilkinson, Bélanger, and Robichon, in later stages of growth the endosteum also contributes to bone formation in the shaft near the epiphyses, this contribution accounting for the widening of the cortex and the narrowing of the marrow cavity at these levels.

In contrast, increase in length of the shaft is endochondral, as was the original development of the bone, for each epiphyseal plate goes through a constant cycle of proliferation, calcification, and absorption of cartilage, with replacement by bone, on the side which is adjacent to the shaft. It has long been known that one end of any long bone with two epiphyses grows much greater in length than does the other one, and this has been said to account for the obliquity of the nutrient canal, which regularly points toward the slower growing end; similarly, where only one epiphysis exists, as in the metacarpals, the nutrient canal is directed toward this epiphysis. Among the large long bones of the limbs, the humerus grows more at its proximal end, and so do the tibia and the fibula, while the radius, the ulna, and the femur grow more at their distal ends.

Payton ('32) emphasized that the greater growth at one end of a long bone is not merely a function of time, but rather depends primarily upon a faster rate of growth at this end. In experiments on pigs, he found that there is, in general, a gradual decrease in the rate of growth of every bone as the animal becomes older, but that, while the rate as a whole decreases, the decrease in rate is less at the faster growing end than at the slower one—in young pigs, the faster growing end grows about twice as fast as the slower growing one, while in older pigs it grows about three times as fast.

Growth in diameter of an epiphysis is periosteal, as is that of the shaft, and growth in length of the epiphysis is endochondral, as is that of the shaft. However, it seems to be amply proved that the so-called epiphyseal plate actually does not contribute to the length of the epiphysis, but only to the length of the shaft (Payton, '32, '33; Siegling). From this standpoint, the epiphyseal plate is poorly named. Payton showed quite plainly in his 1933 paper, describing his feeding of madder to pigs and his study of the growth of the epiphyses, that all new bone formation here that adds to the length of an epiphysis of the bone occurs beneath the articular cartilage, no growth whatever occurring at the part of the bone adjacent to the epiphyseal cartilage. He found that the epiphysis at that end of the shaft that is growing most rapidly itself increases most rapidly in length, but there is no correlation between the total