ANATOMICO-ROENTGENOGRAPHIC STUDIES OF THE SPINE

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Preface

THESE STUDIES were originally undertaken by the author as a means of coordinating the radiographic image with the anatomical structure of the spine.

So many anomalies appeared that it seemed desirable to review the embryological and post natal developmental processes of the structure.

The large number of cadavers from older individuals afforded an excellent opportunity of observing the degenerative changes in the spine incidental to the passage of time.

Of considerable practical interest were the serial studies of patients. These showed the anatomical effect incidental to trauma and the resultant changes thereto which were observable upon subsequent examination. Some of these were followed for periods varying from five to twenty-six years. Certain of the later observations were possible only through the gracious cooperation of radiologists in other distant cities.

Intervertebral foramen encroachment with consequent degenerative changes of the nerve roots, both in the cervical and lumbar regions, presented a worthwhile problem for study. Likewise, the crucial occipito-atlanto-axial region furnished many extremely important observations of interest to neurosurgeons and orthopedists as well as radiologists.

Different types of spondylolysis were observed, two patients being studied serially during the period while they were developing the condition.

Microscopic studies supplied additional information: sections of the intervertebral discs and the apophyseal joints as well as the vertebral bodies affected by various types of disease. Special staining methods were employed to visualize the nerves supplying the ligamentous structures.

These and various other studies of the spine accumulated over a period of some thirty odd years are presented here as a coordination of the roentgenographic image and the actual anatomical condition of that structure.

Acknowledgments

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This is only a partial list of my obligations in the preparation of this work. I am also grateful to those cooperative patients who obligingly returned for followup examinations. To my friends and associates, as well as an understanding wife I am indebted for their kindly and unfailing encouragement. To all of these and others I dedicate this expression of my deepest appreciation.

L.A.H.

Contents

ANATOMICO-ROENTGENOGRAPHIC STUDIES OF THE SPINE

Chapter I

Development of the Spine

A BRIEF REVIEW of spinal development provides a suitable background for later consideration of the anomalies which may be encountered at various periods throughout the life of the individual.

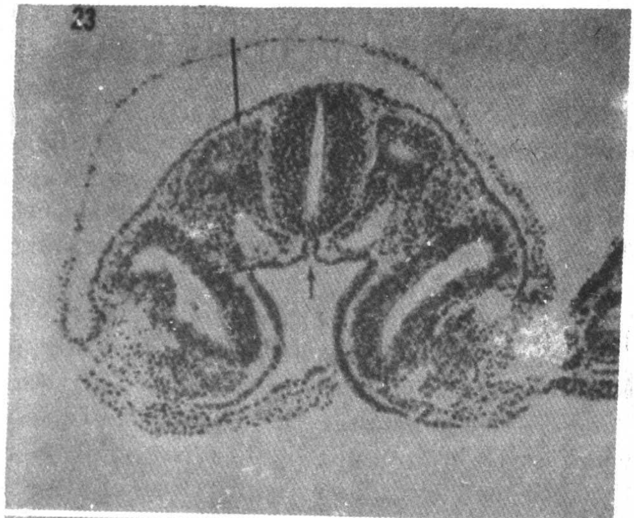
Three overlapping stages are recognized. The blastemal or membranous stage appears in embryos and continues up to about the end of the third month. The chondrogenous stage begins soon after the first month and continues throughout fetal life, while the ossification stage begins in the third month and is incomplete at birth.

The vertebral elements develop about the notochord which is the earliest evidence of the axial skeleton. Sensenig has shown this structure to be an evagination of the roof of the gut, appearing about the twenty-third day (Figure I:1). For the purpose of this discussion, the time mentioned in each instance represents the approximate gestation age from fertilization. Two weeks must be added to give the menstrual age.

By the third week of the membranous stage the dorsal surface of the embryo has invaginated and become closed over to form the neural canal (Figure I:1). Along each side of this structure the mesoderm is becoming segmented into somites separated from each other by the intersegmental blood vessels (Figure I:2). The sclerotome is the ventromedial portion of the somite and is the source of the connective tissue structures of the body. The rapidly multiplying mesenchymal cells migrate in the cephalic, caudal and medial directions joining with cells from the adjacent segments. Those cells which migrate ventrally toward the midline meet with those from the opposite side and surround the notochord. The perichordal tissue mass is thus formed from cells of mesodermal origin. Early disturbance of this growth pattern results in various anomalies to be discussed in Chapters II and III.

At the end of the fourth week, alternating zones of loose and densely packed cells are appearing within the axial mass of mesodermal tissue (Figure I:4). These become the primitive segments. Within the less dense zone—later to form the centrum of the vertebral body—occur the paired intersegmental blood vessels arising from the aorta. Well nourished by these vessels the large cells of the less dense area multiply rapidly to form the centrum. As growth occurs the centrum enlarges at the expense of the denser intervening zones of mesodermal tissue. From these more dense areas there develop: the intervertebral discs, the cranial and caudal surfaces of the vertebral body, the major portion of the neural arches and the ribs. The upper cervical spine and the base of the skull are one continuous mass of mesodermal tissue early before complete segmentation occurs. In (Figure I:4) the segmentation of this area is just beginning.

Separation of the mesodermal tissue into vertebral segments occurs at the chondrification stage about the end of the fifth week after fertilization. Cartilage develops rapidly about the intersegmental artery in the less dense primary



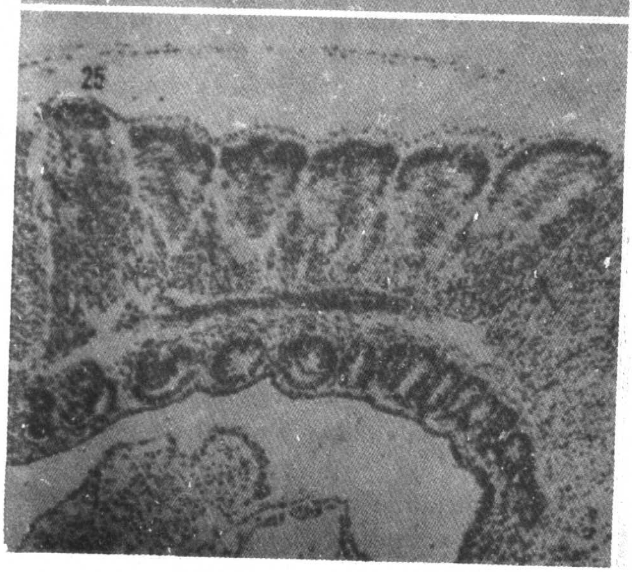


Fig. I:1. Human embryo about twenty-three days post-fertilization, magnification (X100). Transverse section of the upper thoracic region. No. 7611 from Department of Embryology, Carnegie Institution of Washington, comprising sixteen somites. The early notochord appears as a dorsal evagination of the gut roof and lies in contact with the ventral surface of the neural tube (short arrow). The mesoderm of the somite (long arrow) is to be seen with columns of cells migrating in a ventro medial direction toward the newly formed notochord. The long arrow crosses the amnionic sac. (Courtesy of Dr. E. Carl Sensenig, Professor of Anatomy, University of Alabama, Birmingham, and the Carnegie Institution of Washington, Baltimore, Maryland.)

Fig. I:2. Twenty-five day embryo (X95). Longitudinal section in plane shown by long arrow in figure I:1. The somites, composed of segmented mesodermal tissue, are seen at the top underlying the amnionic cavity. Arrow at the right indicates one of the intersegmental vessels arising from the aorta. The dark oval structures below are mesonephrons. (Courtesy of the Syracuse Memorial Hospital Laboratory.)

centrum of the definitive vertebra. The notochord which earlier traversed the centrum, becomes constricted by the rapid growth of the cartilaginous vertebra so that notochordal substance becomes crowded toward the intervertebral discs where it takes part in the formation of the nucleus pulposus (Figures I:6, I:7, and I:8).

Persistence of the notochordal structure may leave a defect through which herniation of disc substance may later occur forming the so-called Schmorl's nodes in the vertebral bodies. The apical ligament of the epitropheus is a functional remnant of the notochord (Figure I:6). Chordomata may subsequently develop from the notochordal rests which occasionally persist in the base of the skull, the sacrum and rarely elsewhere (Figure XVI:11).

Early in the second month, multiple centers of chondrification develop within the less dense portion of each mesodermal segment. These quickly unite to form a complete cartilaginous provertebra comprising centrum, neural arches, transverse and articular processes all in one block (Figures I:5 and I:7B). The early failure of some chondrification centers to fuse may be partly responsible for the development of hemivertebra, cleft vertebra and certain other anomalies to be discussed in Chapters II and III (Figures II:25, II:26 and II:27).

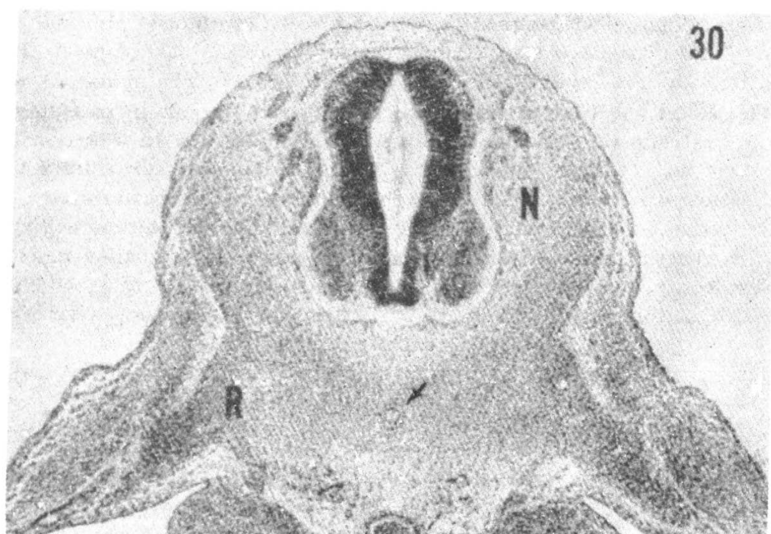


Fig. I:3. Thirty-day, 9 millimeter human embryo (X55). Transverse section of the thoracic region. The notochord (*arrow*) is now surrounded by the perichordal tissue mass made up of mesodermal cells which originated in the sclerotome or ventromedial portion of the somite and migrated to their present position. Condensation of cells which will form the neural arches are seen extending upward along each side of the neural tube. (N). The rib elements are visualized as condensations extending laterally from the mass (R). The artery is visualized in the midline near the bottom of the section. (Courtesy of Dr. E. Carl Sensenig, University of Alabama, Birmingham, and the Department of Embryology, Carnegie Institution of Washington.)

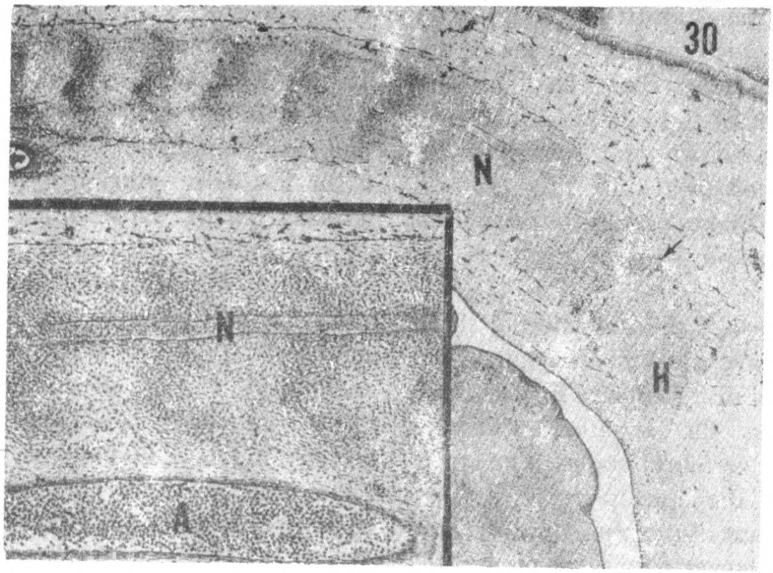


Fig. I:4. Thirty-day, 12 millimeter human embryo (X40). Sagittal section showing longitudinal segmentation of mesodermal tissue as alternating zones of greater and lesser density. This column of mesodermal tissue is seen to be continuous with and of similar character to the hypoglossal mass (H) which later forms the base of the skull. This is separated from the first cervical segment, by a cleft (arrow). The notochord (N), here seen at the second and third segments, appears in other sections to pass directly from the first cervical into the hypoglossal mass where it terminates. In a section cut more laterally there are visualized three nerves arising by multiple fibers from the brain stem and passing separately through this hypoglossal mass to its ventral surface. The inset is another section from the same specimen (X80) showing the notochord (N) passing through the adjacent somites.These mesodermal segments are alternating zones of lesser and greater density. Below is a section of the aorta (A) containing red blood cells, which are nucleated at this period. (Courtesy of Department of Anatomy, New York State College of Medicine.)

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Fig. I:6. Sagittal section, cephalic end, from a 29-millimeter human embryo in the cartilage stage (eight weeks from fertilization) (X22). The rapid growth of the lighter zones has occurred at the expense of the more dense areas. Compared with the thirty-day embryo Figure I:4. The embryo has now at eight weeks developed the cartilaginous centra of the provertebra. Note base of skull (B), anterior arch of atlas (A), separate sections for odontoid (O) and body of the axis and centra for the third and fourth cervical bodies. The notochord is seen passing through the odontoid onto the dorsum of the base of the skull. The central nervous system appears dorsally (N).

Inset; same specimen, section taken somewhat more caudally (X13), showing the manner in which the notochord is being crowded into the disc spaces by the rapid growth of the centra. (From the Department of Anatomy, New York State College of Medicine.)

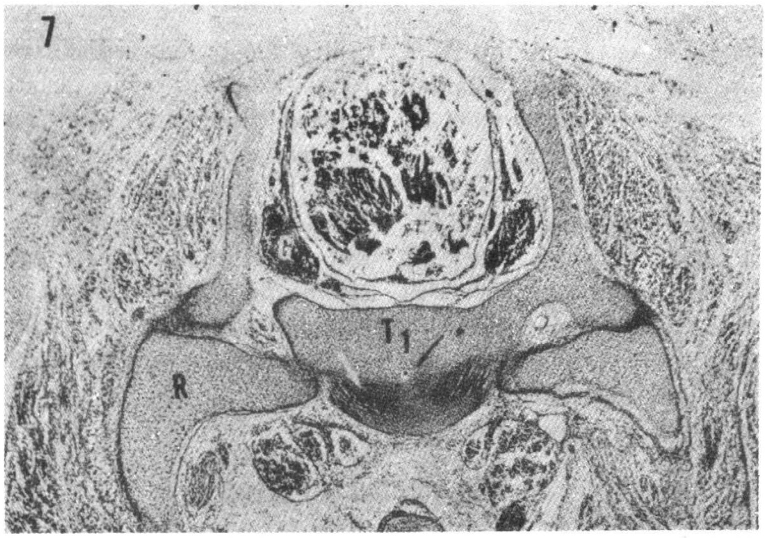
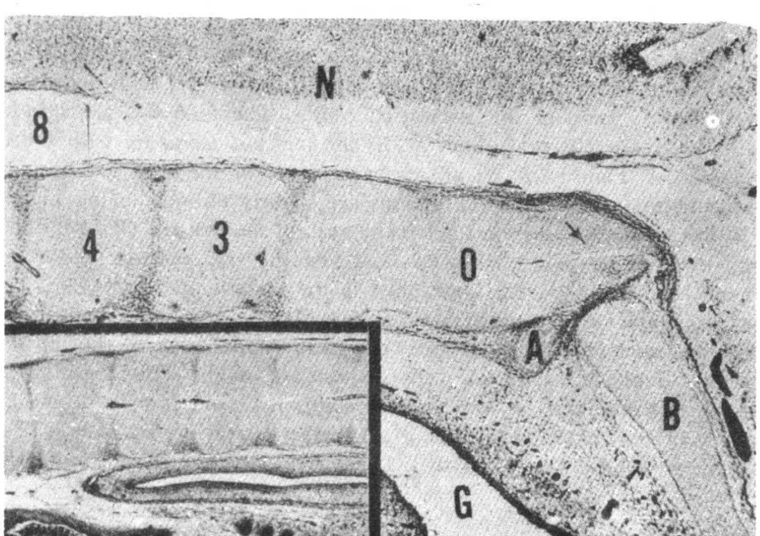


Fig. I:5. Sixteen millimeter human embryo at about seven weeks gestation, in the cartilage stage (X21). The T_1 vertebral body, pedicle, transverse process and neural arch are one continuous cartilage. The arches are not closed over the dorsum of the spinal canal at this period. Dorsal nerve roots are seen entering the spinal ganglia (G). Ventrally are noted annulus fibrosis of the C_7 - T_1 disc (white arrow) while laterally appear the cartilaginous first ribs (R) articulating with the disc and the transverse processes of T_1. The notochord, seen in the mid-line (black arrow), was observed in the serial studies passing through all of the vertebral bodies, the odontoid and into the dorsal surface of the basal cartilage of the skull. The notochord is of greater diameter in the discs than in the mid-centra, where it later becomes entirely absent. There was some calcification in the clavicle but no other structures were visualized on a preliminary radiograph of this embryo. The soft tissues are somewhat disorganized but the cartilage structure is intact. Study of the other serial sections shows the cartilage of the occiput separate from that of C_1 at this time. There is no evidence of a separate rib element forming the anterior part of the upper six cervical transverse processes as held by certain authorities but there is a separate rib element forming the anterior part of the C_7 transverse processes (Figure I:14).



The spinal ligaments and the discs develop from the more dense, darker staining, closely packed cellular structure between the cartilaginous vertebra. (Figures I:4 and I:6).

For each segment there is a rapid enlargement of the cartilage cells and development of the ossification centers in the middle of the centrum and also within each neural arch. At first only calcium is deposited around the enlarged cartilage cells at those three points where the ossification centers will develop (Figure I:7A). There is some variation, but in general ossification will have appeared in each center by the end of the twelth week. On each side there is a center in the neural arch for its pedicle with the transverse and articular processes and also in the midline a center for the vertebral body. This latter may at times be paired, a precursor of hemivertebra (Figure I:10B).

THE VERTEBRA AT BIRTH

Thus the vertebral body of a newborn comprises three bony elements: a spool-shaped centrum and the two sides of the neural arch. These latter consist principally of a pedicle and a spatula-shaped inferior articular process and lamina for each side. The superior articular process is very small. The pars interarticular is completely ossified. In the lumbar region this isthmus is not at all slender at birth as it is in the adult spine after assumption of the upright position. In the sixty-nine fetal and newborn spines examined by this author not a single example of dehiscence in the fifth neural arch was discovered (Figures I:15 and XIII:5).

The medial margins of the two spatula-shaped lamina approach rather closely at the midline posteriorly but do not joint until the first year. The notches seen on the anterior and posterior sur-

Fig. I:7. Ten weeks, 55-millimeter human embryo. The roentgenogram (A) X2 shows centers from C_7 to S_2 for the bodies and many of the vertebral arches. Microscopic study showed a deposit of calcium between and around the enlarged cartilage cells but there was no bone present, the calcium alone permitting radiographic visualization of the skeletal structures. The calcified areas in the neural arches were just dorsal to the transverse processes and all of the ribs were calcified.

B. Transverse section, same specimen (X14) shows the cartilaginous T_1 vertebral body, pedicle and transverse process (P) with calcific deposit (X) showing black on right side at the future location of the ossification center. The bifid C_7 cartilaginous neural arch is closed over but not continuous across the midline. Compare with the condition three weeks earlier, Figure I:5. At all levels the sides of the arch are united only by fibrous tissue in the midline. These sections are slightly oblique, being higher on the left side. In this section one sees on the left the head of the first rib (R) and the posterior articulation between the seventh cervical and first thoracic articular processes *(arrow)*.

C. Same specimen, lumbar area sectioned in the sagittal plane (X15.5). There were six lumbar segments. Other more lateral sections of the series showed the lowermost to be sacralized on one side only. Cartilage cells in the midportion of the centra are very large. The calcium deposit about the cells is visualized on the stained section as a dense black shadow but there are no bone cells present. By rapid growth of the centra the notochord has become crowded into the discs. In the fourth lumbar body it has partially persisted as a "notochord streak" *(arrow)*. These areas may constitute points of weakness

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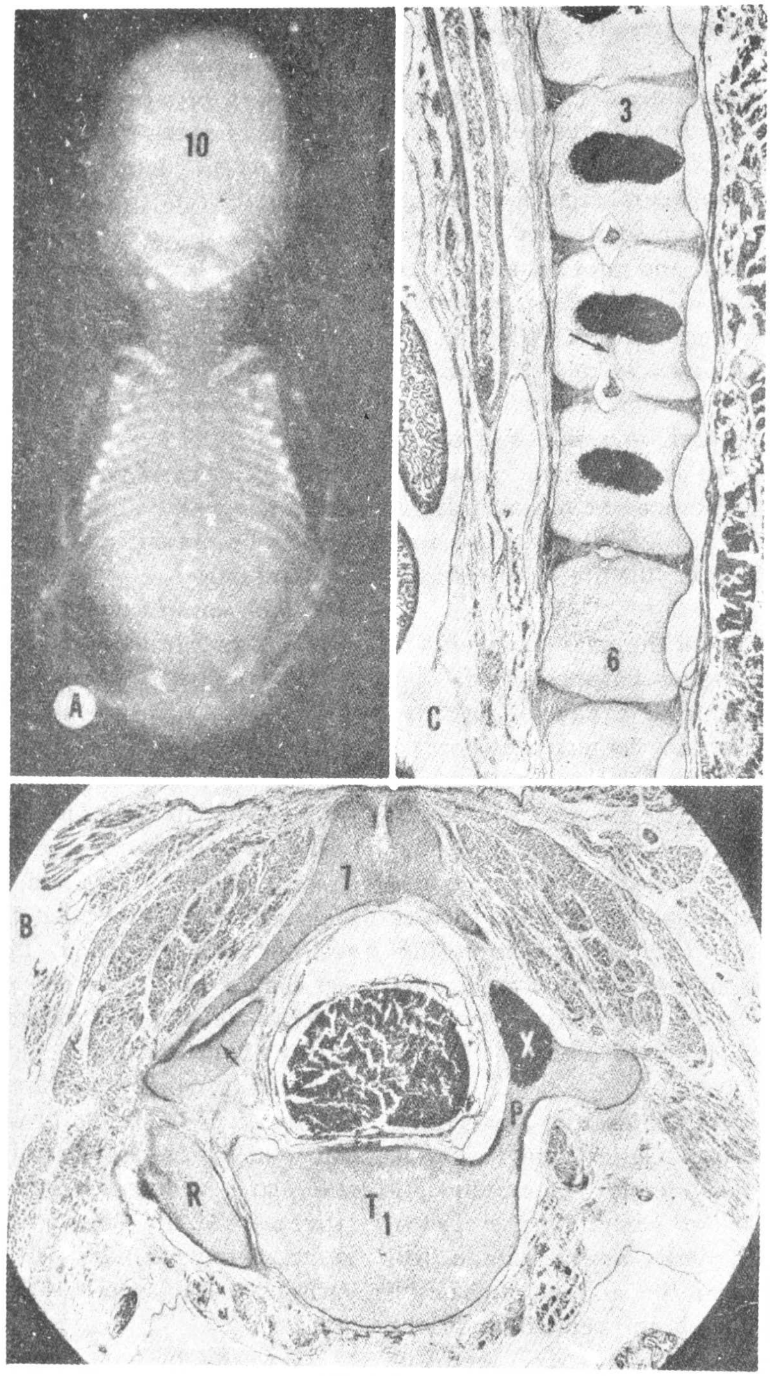

which allow subsequent herniation of the disc substance to occur. Dorsally (right side of illustration) the posterior longitudinal ligament is attached only at the discs while ventrally the anterior longitudinal ligament is more closely applied to the vertebral body and is continuous with the anterior disc margins.

faces of the vertebral body are spaces occupied by blood vessels (Figures I:10 and I:11). The pair of small openings seen near the midline on the frontal radiograph are venous channels on the posterior surface of the vertebral body.

Below C_2 the neural arch closes in the midline during or soon after the first year but the axis and atlas close at about the second and fourth years respectively. However at times the first arch may remain open. (Figure III:35). Closure of the neurocentral union between the pedicle and vertebral body does not occur until the fourth or fifth year. These latter junction lines may be mistaken for a fracture in a young child or they may even persist into adult life (Figures I:11 and I:14).

Ossification of the atlas, axis, sacrum and coccyx is somewhat specialized. The atlas develops from a pair of laterally placed ossification centers which give origin to the lateral masses and the posterior arch. A separate ossification center usually appears at the midpoint of the anterior arch cartilage during the first year. This arch and the lateral masses fuse about the fifth or sixth year (Figure I:14). If the anterior arch of the atlas does not develop the two sides of the structure may remain separate (Figure III:29).

The axis originates from a pair of lateral ossification centers for the arch, a midline body center, sometimes double, and a paired center for the epistropheus. These latter appear in the fifth month of fetal life and later coalesce. They unite with the remainder of the axis during the third or fourth year (Figures I:16 and III:3). The tip of the odontoid arises from a secondary center which appears by the fourth year and fuses about the twelfth year (Figure I:22).

The sacrum is formed from five segments each corresponding to the separate elements of a single vertebra. These fuse into a single mass between the 12th and 25th year. In addition, two or three pairs of "costal" elements develop in front and later fuse to become the ala of the sacrum. There are also epiphyseal plate structures between the different segments as well as within the sacroiliac joints (Figures I:14, I:20, I:21 and II:21).

The coccyx is usually cartilagenous in the newborn, but an ossification center may be present in the proximal segment at birth.

By the seventh fetal month the osteoblastic center of the vertebra has acquired epiphyseal cartilage plates upon its cephalic and caudal surfaces. The growth area appears as a zone of columnar cartilage between the flat cartilage epiphyseal plate and the underlying invading bony trabeculae of the vertebra. Growth occurs at this zone by enchondral ossification, first calcifying and then ossifying (Figure I:12). These epiphyseal plates curve over the edges of the vertebra and dip into the notches which appear about the upper and lower margins of that structure within the first year (Figure I:17B). Radially placed vessels course along the surfaces of the epiphyseal plates within the cartilage. These latter are radially fluted for strength and fit accurately into grooves on the end surfaces of the vertebrae (Figures I:17F and I:19).

A wealth of blood vessels enter the centrum through the dorsal and ventral surfaces of the vertebral body (Figure I:9). Vessels passing from the vertebral