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The arterial anatomy of the developing human dorsal and lumbar vertebral body. A microarteriographic study

J. F. RATCLIFFE*
Department of Radiodiagnosis, University of Bristol

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INTRODUCTION

The arterial anatomy of the normal adult human lumbar vertebral body has been described in some detail (Mineiro, 1965; Ratcliffe, 1980). The intra-osseous arteries arise from two anastomotic systems, one on the anterolateral vertebral surface and another within the spinal canal. These communicate at the intervertebral foramina. The principal intra-osseous arteries are distributed into three horizontal layers, one equatorial and a metaphyseal layer near each end. The form of the principal arteries is similar; each has a relatively long, wide, straight and unbranching centripetal stem with a coiled pre-terminal segment and multiple centrifugal branches. Peripheral arteries are widely distributed in older specimens and these are dissimilar in that they have short, narrow stems and centripetal branches which supply the outer collar of the vertebral body. The concept of a zoned distribution of blood supply within the vertebral body has been proposed (Ratcliffe, 1980), based on this anatomy. The central core, extending from disc surface to disc surface, which lies behind the mid-axial point of the vertebral body, is supplied by the equatorial arteries; an annulus at each end adjacent to the disc is supplied by the metaphyseal arteries; the surrounding collar from disc to disc is supplied by the peripheral arteries. Thus, the region of vertebral body adjacent to the nucleus pulposus is supplied by equatorial arteries and the region subjacent to the annulus fibrosus is supplied by the metaphyseal arteries and peripheral arteries.

The arterial anatomy of the immature vertebral body has been variously described (Lexer, Kuliga & Turk, 1904; Hanson, 1926; Bohmig, 1930, Willis, 1949; Furguson, 1950; Mineiro, 1965; Guida, Cigala & Riccio, 1969). There was some, but limited, agreement in the findings of these investigators. Most reported their findings in a single specimen and only one (Mineiro) reported different findings in several specimens of different ages.

Examination of the anatomy during maturation might reveal the evolution of the adult anatomy and would be a basis for determining which features in the adult might be due to senescence. This paper reports work which shows changes in the arterial anatomy occurring during development.

* Present address: Department of Radiodiagnosis, Booth Hall Children's Hospital, Charlestown Road, Manchester M9 2AA.

Table 1. *Details of material examined*

Age months (weeks)	Sex	Dorsal vertebrae (20)					Lumbar vertebrae (40)					Vertebrae per subject
		8	9	10	11	12	1	2	3	4	5	
18	F	—	—	—	—	H	H	S	S	S	S	6
F(29)	F	C	C	C	C	C	C	S	S	S	H	10
3	M	—	—	—	—	C	C	C	H	H	H	6
F(36)	F	C	C	C	C	C	H	H	S	S	S	10
F(32)	M	S	S	S	S	H	H	C	C	C	S	10
6	M	—	—	—	H	C	C	C	C	S	H	7
84	M	—	—	—	—	H	H	H	S	S	S	6
180	M	—	—	—	—	—	C	S	H	H	S	5
Total												60

Age indicated in months, except for the three fetuses, which are prefixed F, where the age of gestation, from the first day of the last menstrual period, is given in weeks, in parentheses.

Sixty dorsal and lumbar vertebrae were studied, of which 17 were sectioned horizontally, H; 22 were sectioned coronally, C; 21 were sectioned sagittally, S.

MATERIAL AND METHODS

Sixty vertebrae were examined from eight subjects aged from 29 weeks gestation to 15 years. Post mortem examination confirmed brain injury as the cause of death in all subjects. Details of age, sex and vertebrae examined are set out in Table 1.

The aorta of each subject was cannulated and injected at physiological pressure with a 50 % suspension of Micropaque (Damancy & Co. Ltd), while the aorta and lumbar region were still intact. This technique results in the filling of 90 % of histologically identifiable arteries (Ratcliffe, 1978).

After injection, the spines were excised, radiographed and fixed in normal formol saline. They were decalcified in 10 % nitric acid. The vertebral bodies were cut horizontally, coronally or sagittally into sections 0·5 mm to 10 mm thick.

These sections were radiographed on fine emulsion X-ray film using a low Kv technique.

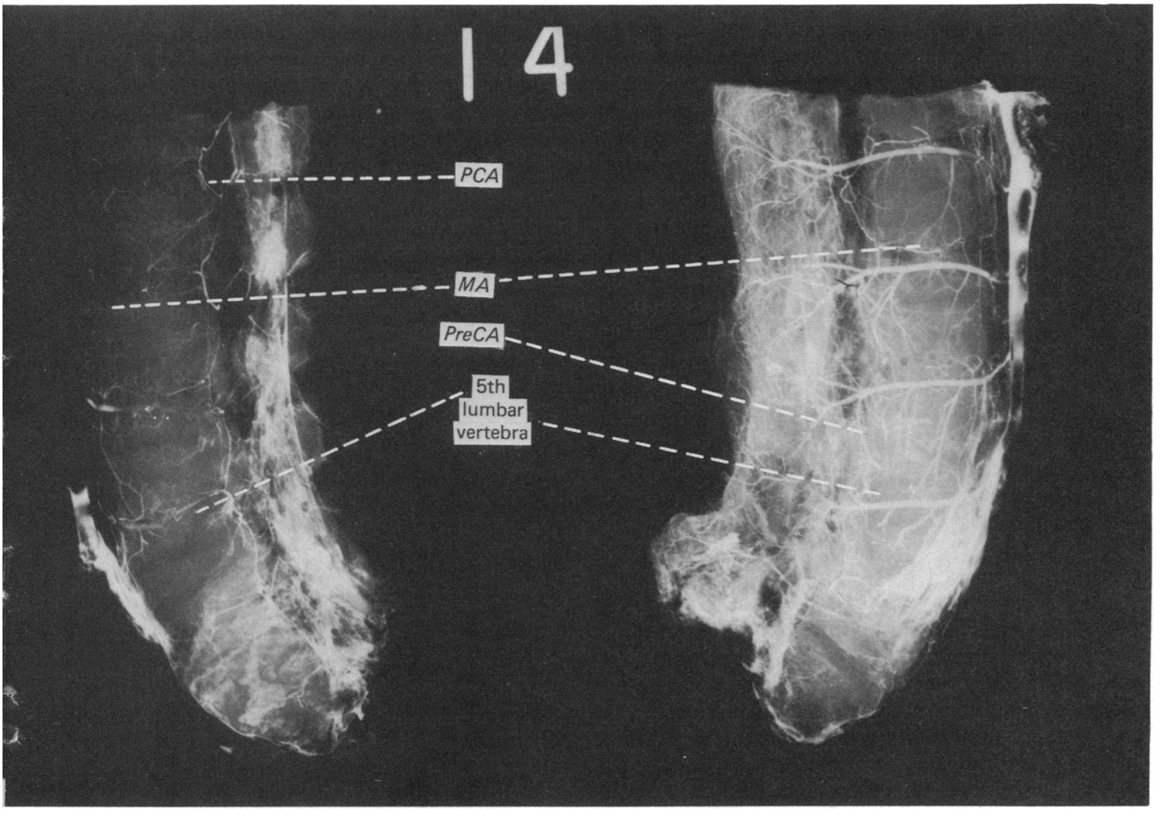
RESULTS

Extra-osseous arteries

The segmental arteries, including the arteria lumbalis ima, were well developed and equal in size in all fetuses and infants (Fig. 1). In the 7 and 15 years old subjects, the segmental artery of the fifth lumbar vertebra was smaller than other lumbar arteries. The segmental artery of the fifth vertebra arose from the median sacral artery in all eight subjects. The upper four lumbar and the intercostal arteries arose from the back of the aorta.

Perichondral arteries arose from the upper and lower borders of each segmental artery as it lay on the vertebral body. They passed upwards and downwards, crossing the intervertebral disc to anastomose with the perichondral arteries of vertebrae above and below. The number of perichondral arteries varied between 8 and 20 for each segmental artery; generally, the fetuses had fewer arteries than the older subjects.

Branches of the perichondral arteries anastomosed on the surface of the vertebral bodies. These anastomoses appeared irregular and near the equator in the 29 weeks fetus (Fig. 2). In the older fetuses and infants, they were more regular and organized.



In all the Figures, left and right refer to the reader's left and right side of the illustration.

Fig. 1. Radiograph of the lumbosacral spine taken from an 18 months old child and showing lumbar vertebrae 2, 3, 4 and 5. After complete decalcification, the ossification centre is less radio-opaque than the surrounding cartilage and disc. The spine has been divided sagittally and the soft tissue almost completely dissected off the specimen on the left. The metaphyseal anastomoses (*MA*) with branches crossing the disc spaces are shown. The postcentral anastomosis (*PCA*) is shown. The segmental artery of the fifth lumbar vertebral body, arising below the aortic bifurcation, is shown to be the same size as other lumbar segmental arteries. The precostal anastomosis (*PreCA*) is shown joining the segmental arteries of the fourth and fifth vertebral bodies.

In the 6 months old infant, the arteries were organized into two horizontal horseshoe shaped anastomoses which lay on the anterolateral surface of the vertebral body and crossed the mid-line behind the aorta (Fig. 3). The horizontal anastomosis which lay near the upper disc was better defined and more regular than that which lay near the lower disc. In the adult, these horizontal anastomoses have been called metaphyseal anastomoses (Ratcliffe, 1980). A lattice-like anastomosis on the anterolateral surface of vertebral bodies was thus formed in late fetal life. Longitudinal perichondral arteries joined segmental arteries to metaphyseal anastomoses and also joined metaphyseal anastomoses of adjacent vertebrae across the disc spaces. This lattice anastomosis persists into adult life.

In the infants and children, there was usually a direct and prominent anastomosis between the segmental arteries of the fourth and fifth lumbar vertebra. This lay near the posterior margin of the vertebral body (Fig. 1). It persists into adult life and has been called the precostal anastomosis (Ratcliffe, 1980).

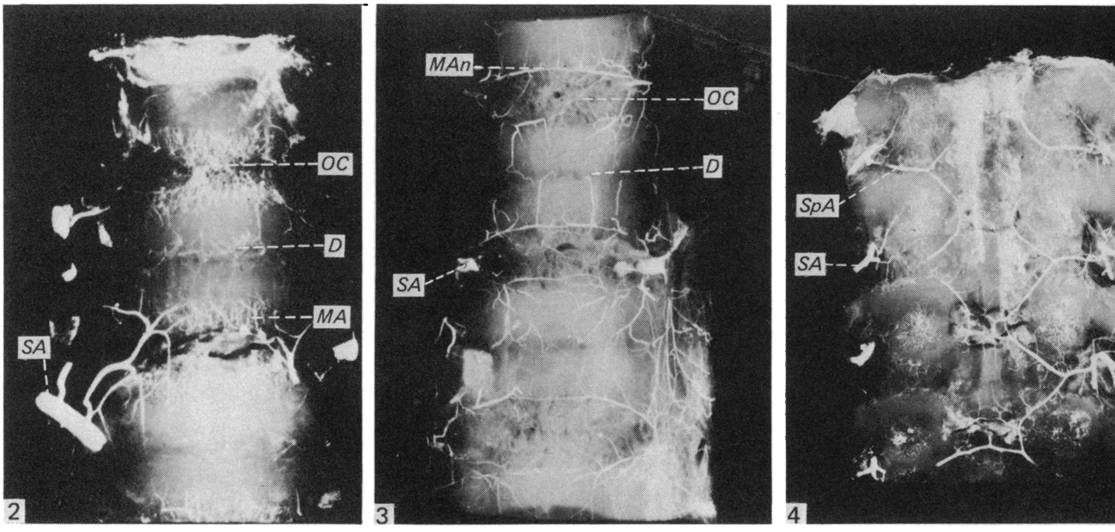


Fig. 2. Radiograph of the most anterior coronal section of two decalcified vertebral bodies from a 29 weeks fetus. The ossification centres (*OC*) are highly vascular and, after decalcification, are the least dense parts. The discs (*D*) are less dense than the hyaline cartilage of the vertebral body. The irregular formation of the metaphyseal anastomosis and oblique metaphyseal arteries (*MA*) are shown. Arteries from the metaphyseal vessels cross the disc in the adventitia to form an anastomosis between the segmental vessels. × 3.

Fig. 3. Radiograph of the most anterior coronal section of three decalcified vertebrae from a 6 months old child. The ossification centres are less opaque than other parts and appear porous. Segmental arteries (*SA*) are shown giving rise to perichondral arteries which form metaphyseal anastomoses (*MAn*) at the levels of the upper and lower margins of the ossification centres. The cephalad metaphyseal anastomosis is better developed than the caudad. Branches from the anastomoses cross the disc spaces (*D*) and also enter the ossification centres (*OC*). × 2.

Fig. 4. Radiograph of the most posterior coronal section of the decalcified lowest four dorsal vertebral bodies of a 36 weeks fetus. The segmental arteries (*SA*) are seen to give origin to the spinal arteries (*SpA*) which divide into ascending and descending branches. These anastomose near the nutrient foramen of each vertebral body. × 3.

The segmental arteries divided into four, five and six branches at the intervertebral foramina. The most ventral, the spinal artery, passed medially, hooked over the free border of the posterior longitudinal ligament and divided into an ascending and descending branch. The ascending branch passed towards the centre of the dorsal surface of the same vertebra and the descending branch towards the centre of the dorsal surface of the vertebra caudad. The ascending branch anastomosed with the descending branch from the cephalad segmental artery and the descending branch anastomosed with the ascending branch from the caudad segmental artery. They also anastomosed with their contralateral counterparts at the centre of each dorsal surface. In the fetuses, and in the children up to the seven years old, this longitudinal anastomosis, the postcentral anastomosis, was formed by a series of nearly square rhomboids (Fig. 4). In the fifteen years old, the rhomboids had elongated and this pattern persists into adult life.

The only extra-osseous communication between the anterolateral and post-central anastomoses was the short spinal artery at each intervertebral foramen.

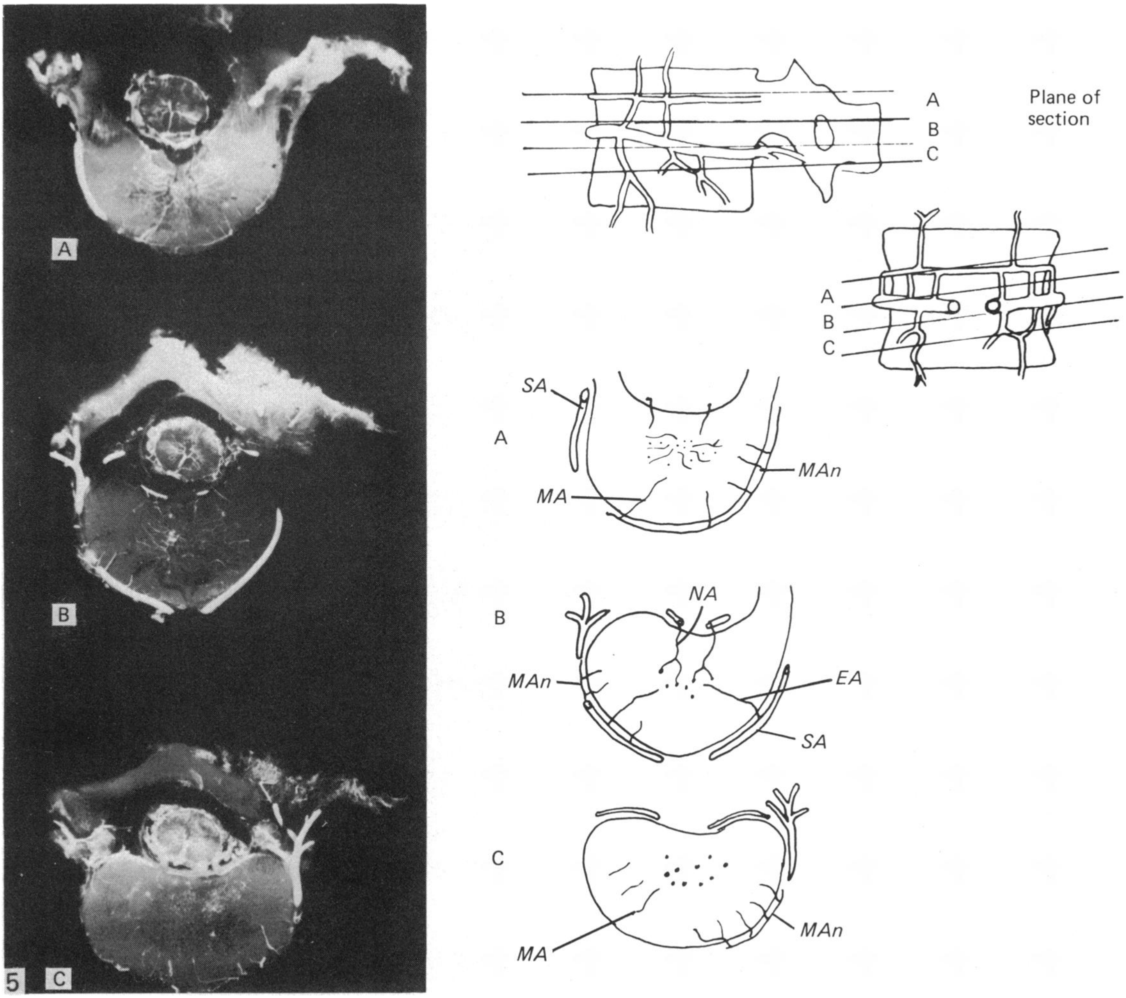


Fig. 5. Radiographs, with accompanying diagram, of three consecutive sections through the fifth lumbar vertebral body from a fetus of 36 weeks. The sections are cut slightly off the horizontal. The upper section (A) passes through the upper metaphysis, but includes part of the segmental artery (*SA*) on the left. The upper metaphyseal anastomosis (*MAn*) can be seen in the perichondrium on the right. From it, metaphyseal arteries (*MA*) extend towards the centre, but pass above the ossification centre out of the plane of section and are thus truncated. The middle section (B) passes through the equator and into the lower metaphysis on the left. The nutrient arteries (*NA*) are shown. Most of both segmental arteries (*SA*) are shown. The inferior metaphyseal anastomosis (*MAn*) can be seen in the gap where the segmental artery has been included in the upper section. Anterolateral equatorial arteries (*EA*) are shown. Some metaphyseal arteries which converge from the periphery towards the lower pole are truncated as they pass out of this section into the next. The lowest section (C) shows the irregular metaphyseal anastomosis (*MAn*) on the right. On the left, the terminal central portions of the metaphyseal arteries (*MA*) from the section above are shown. Also shown are the mainly transversely sectioned vessels of the ossification centre. These are axial branches of the equatorial arteries. × 2.

Intra-osseous arteries

Four or more arteries entered each vertebral body at its equator.

Two, the nutrient arteries, arose posteriorly from the postcentral anastomosis at the point of convergence of the ascending and descending branches. The nutrient arteries were generally equal in size in the fetuses and infants (Fig. 5) but, in the

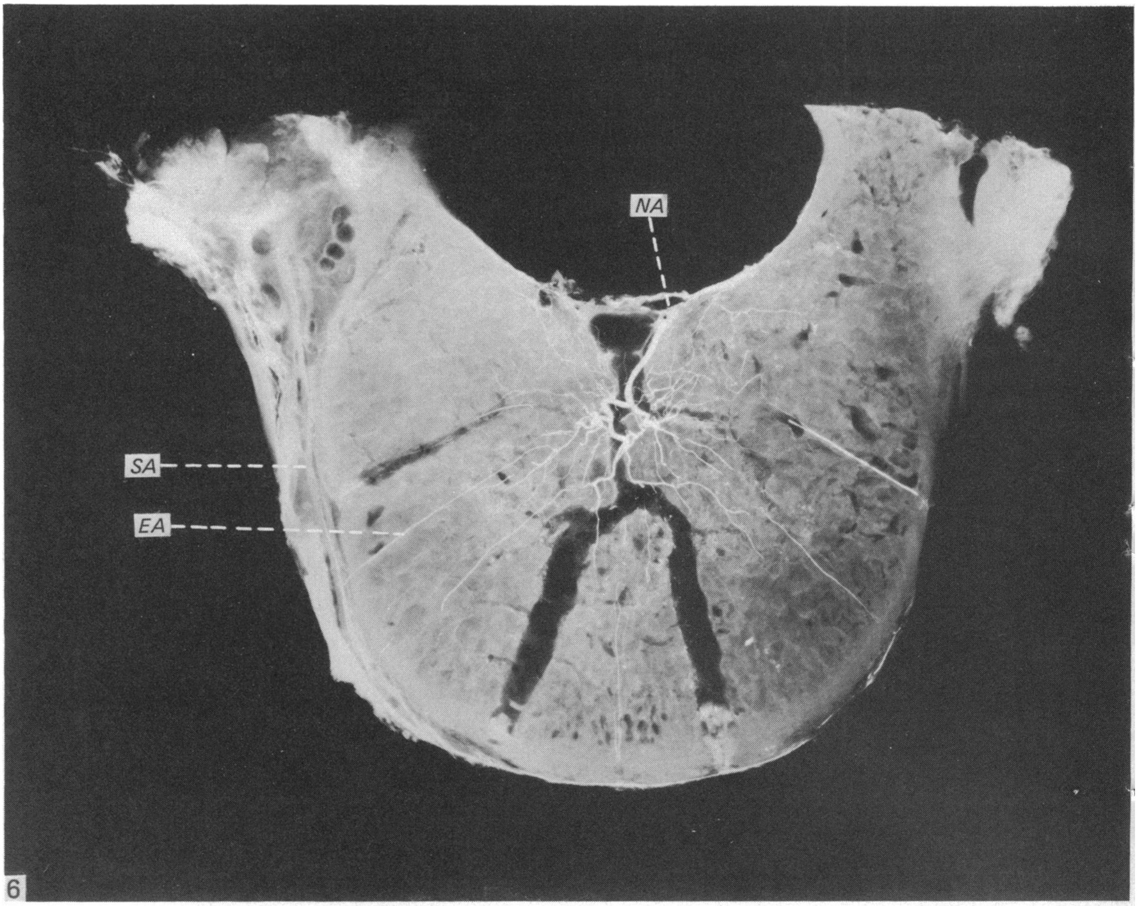


Fig. 6. Radiograph of a horizontal section through a vertebral body of a 15 years old boy. One nutrient artery (*NA*) is dominant and is seen on the right of the cavity of the nutrient foramen. This cavity is the venous channel which anastomoses with two large venous sinuses. The section is slightly oblique and, on the left, the anterolateral equatorial artery (*EA*) can be seen arising from a collapsed segmental artery (*SA*) and anastomosing with branches of the nutrient artery. A few of the upper metaphyseal arteries can be seen around the body, but their origins from the metaphyseal anastomosis are not in this section because the vertebral body is biconcave at this age. The long, straight, unbranching stems of all these arteries and the centrifugal direction of the terminal branches is demonstrated. The nutrient artery breaks up behind the mid-point of the vertebral body.

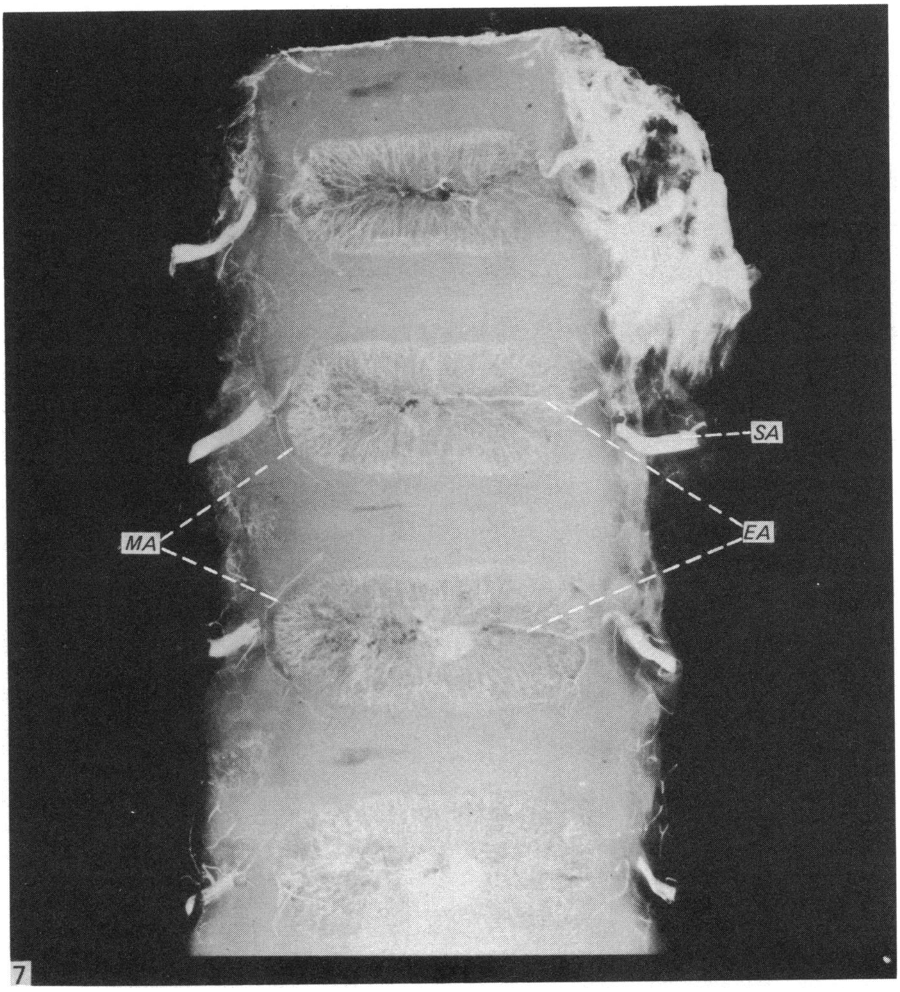


Fig. 7. Radiograph of a coronal section through the bodies of four dorsolumbar vertebrae from a 29 weeks fetus. The ossification centres are highly vascular, with centrifugal, mainly axial, branches of the equatorial vessels. Segmental arteries (*SA*) lie adjacent to vertebral bodies. The upper vertebral body is sectioned behind the mid-point. The termini of the two nutrient arteries are shown closely related to the larger venous channels. The second and third vertebral bodies from the top each show an anterolateral equatorial artery (*EA*) on the right. The third and fourth vertebral bodies are incompletely decalcified and irregular, opaque calcification is shown centrally. Metaphyseal arteries (*MA*) run obliquely, lateral to the ossification centres and lie separate from the vessels of the centres in all four vertebrae. ×4.

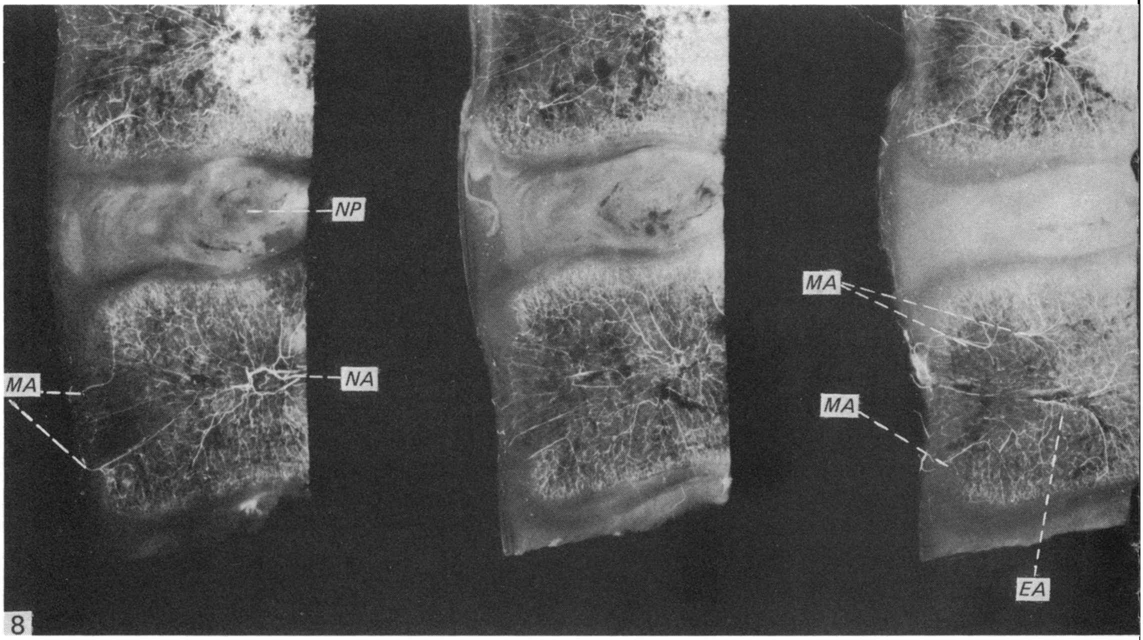


Fig. 8. Radiograph of sagittal sections through part of the fourth and fifth lumbar vertebrae of a 7 years old child. The backs of the vertebral bodies had been cut off for a coronal section. The left section includes the mid-line and the other two are consecutive lateral sections. The mid-line section (to left) shows the termination of the nutrient arteries (*NA*) forming a loop with many centrifugal branches, subjacent to the nucleus pulposus (*NP*). Metaphyseal arteries (*MA*) are seen entering from the front. The next two sections show metaphyseal arteries and the antero-lateral artery (*EA*) is shown in the third section. The third section also shows metaphyseal arteries (*MA*) which had originated lateral to this section.

fifteen years old boy, one in each vertebral body had usually become dominant (Fig. 6). This inequality is maintained into adult life.

One, or occasionally two or three, arteries arose from each segmental artery on the anterolateral surfaces at the equator and passed medially into the ossification centre (Figs. 5, 6, 7). In the fetuses and infants, these anterolateral equatorial arteries lay in the coronal plane (Fig. 7), whereas, in the seven and fifteen years old, they ran dorsomedially (Fig. 6).

None of the equatorial branches divided within the cartilaginous shell of the vertebral body, but they branched profusely within the ossification centre. In the fetuses, these branches were directed towards the disc, i.e. largely axially (Fig. 7). In older subjects, these branches were radial in all directions, i.e. globally centrifugal (Figs. 6, 8). In the seven and fifteen years old subjects, the central group of axially directed branches had migrated dorsally with the medial ends of the anterolateral equatorial arteries. The equatorial arteries thus broke up behind the mid-point of the vertebral body. This area lies subjacent to the nucleus pulposus (Fig. 8).

Ten to twenty arteries arose from the metaphyseal anastomosis on the anterolateral surface and four or five from the postcentral anastomosis near the metaphysis to enter the vertebral body. These persist into adult life and have been named metaphyseal arteries (Ratcliffe, 1980). In the 29 weeks fetus, the metaphyseal arteries were simple loops arising from the irregular network near the equator. They passed obliquely towards the centres of the discal surfaces and lay entirely outside the ossification centre (Figs. 7, 9).

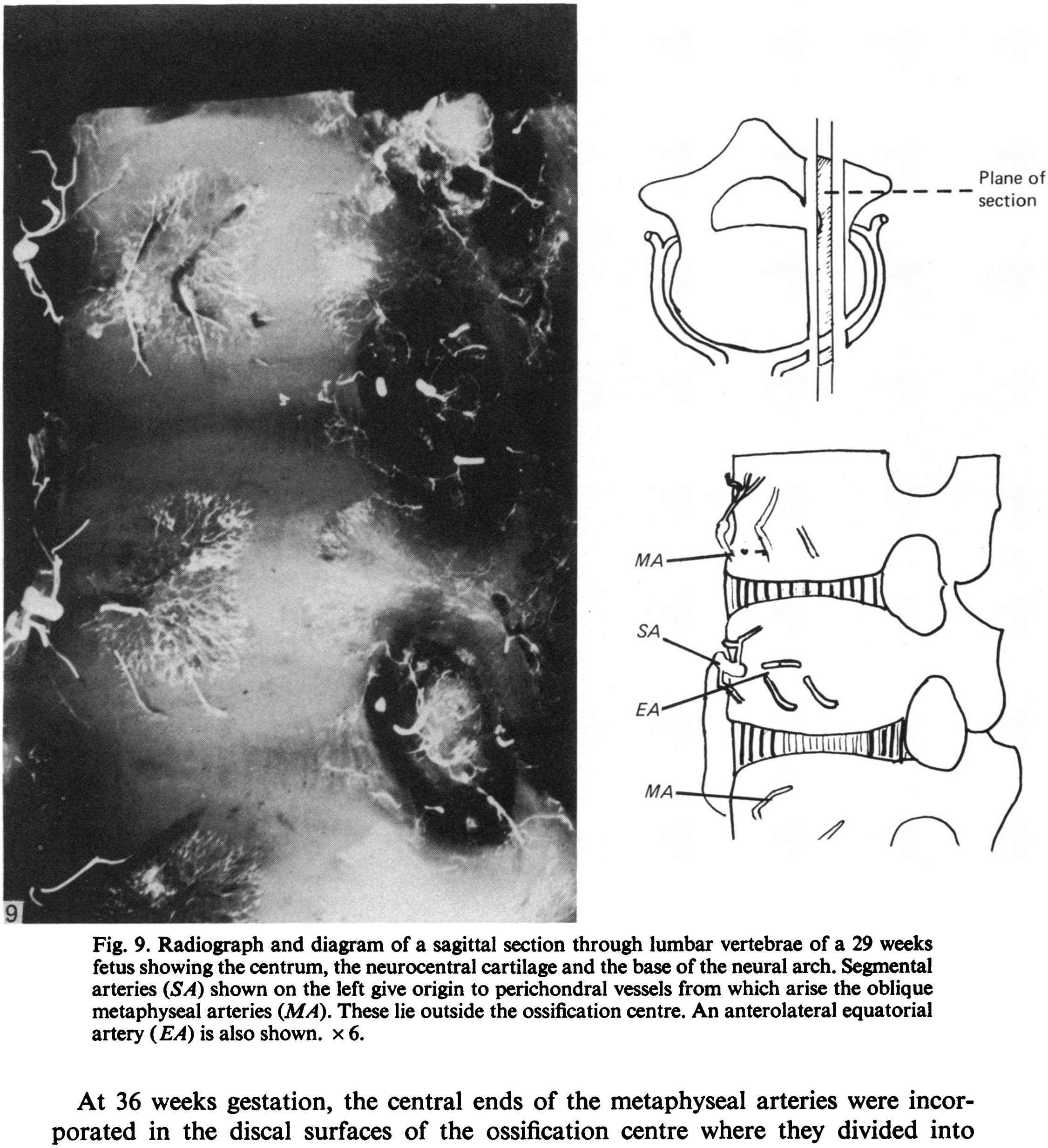


Fig. 9. Radiograph and diagram of a sagittal section through lumbar vertebrae of a 29 weeks fetus showing the centrum, the neurocentral cartilage and the base of the neural arch. Segmental arteries (*SA*) shown on the left give origin to perichondral vessels from which arise the oblique metaphyseal arteries (*MA*). These lie outside the ossification centre. An anterolateral equatorial artery (*EA*) is also shown. × 6.

At 36 weeks gestation, the central ends of the metaphyseal arteries were incorporated in the discal surfaces of the ossification centre where they divided into centrifugally directed branches. The branches of the metaphyseal arteries anastomosed with each other. The metaphyseal arteries supplied an annulus of the ossification centre in the sub-discal region around the central core supplied by the cephalocaudad branches of the equatorial arteries.

In the fetuses, the metaphyseal arteries ran obliquely towards the discal surfaces, but by 18 months these arteries had become horizontal when the metaphyseal anastomoses had become fully developed. The metaphyseal arteries remained parallel to the discal surface into adult life.

In older specimens, a smaller proportion of the vertebral body was formed by the cartilage anlage. In the fifteen years old, this was reduced to a thin shell of a few millimetres (Figs. 10, 11, 12). Projections of cartilage around the bases of the meta-

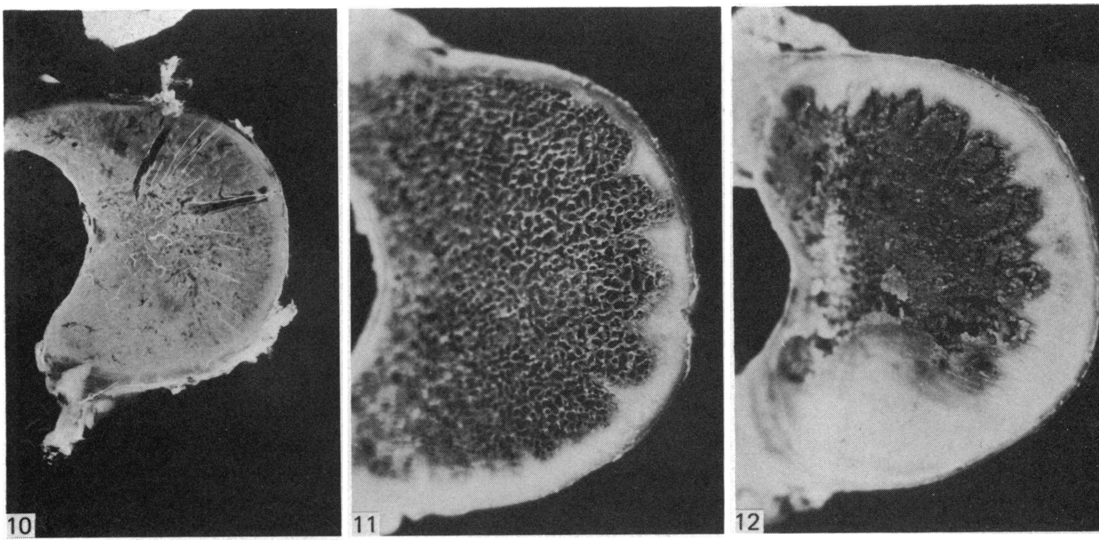


Fig. 10. Radiograph of a slightly oblique horizontal section to include the lower metaphysis of a vertebral body from a 15 years old boy. This section is immediately caudal to that illustrated in Fig. 6. The metaphyseal arteries are hairpin shaped and have centrifugal terminal branches. The irregular vessels seen behind the mid-point of the body are the termini of the equatorial arteries, with which the metaphyseal arteries anastomose. The peripheral ring of cartilage is also shown, as is the scalloped margin of the ossification centre with projections of cartilage at the origins of the metaphyseal arteries.

Fig. 11. Photograph of a horizontal section of the decalcified vertebral body of a 15 years old boy, near the metaphysis. This shows the scalloping of the encapsulating cartilage by the ossification centre.

Fig. 12. Photograph of a section of decalcified vertebral body, immediately discal to the section shown in Fig. 11. Part of the disc is included at the bottom. The end plate is scalloped correspondingly to the scalloping in the metaphysis.

physeal arteries were found (Figs. 10, 11) and those projections extended into the sub-discal regions (Fig. 12).

In the seven and fifteen years old subjects, the metaphyseal zones were highly vascular, but no artery was seen which could be considered to enter an epiphysis.

The basal parts of the neural arches were incorporated into the vertebral body. These parts were supplied extra-osseously by the same arteries which supplied the adjacent perichondrium on the centrum. These were branches of the descending branch of the spinal artery on the posteromedial surface and branches of the upper metaphyseal anastomosis on the lateral surface. No intra-osseous artery was seen to cross the neurocentral cartilage.

These observations of the intra-osseous arteries are summarized in Figure 13.

DISCUSSION

Wiley & Trueta (1959) described, in the adult and adolescent spine, an anterolateral extra-osseous anastomosis connecting adjacent metaphyseal regions across the intervening disc. They postulated that this was the route of spread of haematogenous vertebral osteomyelitis. This connexion, which has been demonstrated in all the spines in this study, became fully developed in the six months old infant and persisted relatively unchanged into adult life.

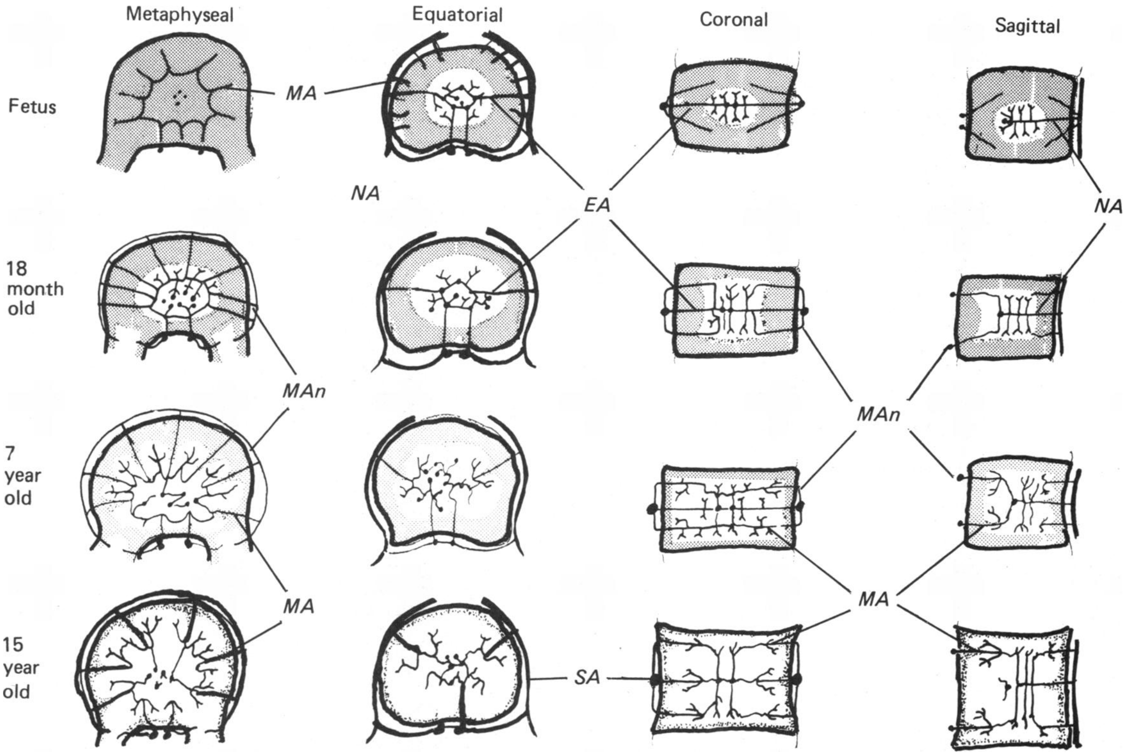


Fig. 13. Diagrams of the arterial supply to the vertebral body during development. *MA*, metaphyseal artery; *MAn*, metaphyseal anastomosis; *SA*, segmental artery; *NA*, nutrient artery; *EA*, anterolateral equatorial artery.

The unusual shape of the intra-osseous arteries, with their long, straight, unbranching stems and centrifugal terminal branches, has been shown to persist into adult life (Ratcliffe, 1980). This shape would evolve if growth of the vertebral body occurred by the surface accretion of avascular cartilage without significant interstitial growth of the ossification centre. Thus, the vertebral body increases in diameter with the central terminations of the intra-osseous arteries relatively fixed. This results in radial elongation of the intra-osseous arteries. The elongated stems are unbranching because vertebral body growth results from the accretion of avascular cartilage. Growth of the ossification centre occurs as a secondary phenomenon by the centrifugal advance of its periphery. The branches of the intra-osseous arteries follow the advancing zone of ossification and are thus centrifugal. The leading edge of the ossification centre bulges between the metaphyseal arteries scalloping out the cartilage. Projections of cartilage surround the origin of each metaphyseal artery, and because they extend into the disc, account for the serrated edges of dried vertebral bodies from adolescent skeletons. These serrations probably increase the strength of the osseo-cartilaginous junction during adolescence.

During development, the axially directed branches of the equatorial arteries become relatively more posterior, and the intra-osseous arteries from the anterolateral surface become longer than those of the posterior surface (Figs. 6, 10). These observations indicate that growth in diameter of the vertebral body takes place mainly through growth of the anterolateral surfaces. This conclusion was also reached by Erdheim (1931) who made observations on the growth of the vertebral body of an acromegalic

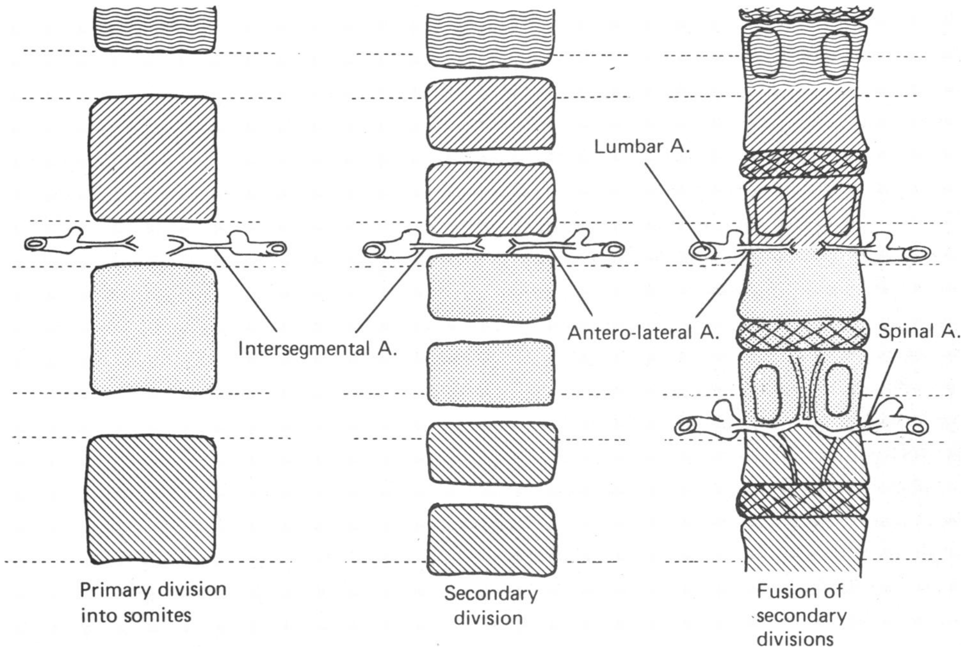


Fig. 14. Diagram of the embryological development of the vertebral body. Each type of shading represents tissue derived from a different mesenchymal somite. This shows how the intersegmental arteries become apparent segmental arteries. The central branches of the intersegmental vessels are the equatorial arteries. The spinal artery and its ascending branch to the nutrient foramen mark the line of original cleavage on the dorsum of the vertebral body.

man, and Knutson (1961) who used a Schmorl's node as a marker in the vertebral body of an adolescent.

The vertebral body in the fetus is wider than it is high; during infancy it is cuboidal; as it further develops it grows in height more than in width. This is reflected in the change in shape of the postcentral anastomosis, from a series of equilateral rhomboids to a longitudinal series of H-shaped anastomoses in the adult.

The migration towards the sub-discal regions of the metaphyseal anastomoses and metaphyseal arteries indicates that vertical growth of the anterolateral surface takes place in the region of the equator in the fetus and young child. This corresponds in time with the change in shape of the lumbar spine from the fetal kyphosis to the straight spine of early childhood.

Subsequently, the distribution of the arteries in three horizontal planes remains relatively constant, even though the vertebral body increases threefold in height. This constant relative position of the metaphyseal and equatorial arteries suggests that growth in height after six months occurs uniformly throughout the vertebral body and not from any putative physis plate in the sub-discal region. No true epiphysis can therefore exist which could result in growth. No epiphyseal arteries were seen in any specimen in this series. Epiphyseal arteries have been described in immature animals with definite corporal epiphyses, e.g. rabbits (Amato & Bombelli, 1959; Stillwell, 1959) and mice (Vasiliev & Vladimirov, 1968) but not in monkeys (Stillwell, 1959).

There are, thus, gradual and significant changes in the arterial anatomy of the vertebral body from late fetal life to adolescence. The arterial anatomy in the adolescent is very similar to that of the adult, but there are two major differences. In the adult, there are peripheral arteries, which are short stemmed and have centripetal branches, and there are preterminal coils on the metaphyseal and equatorial arteries (Ratcliffe, 1980). These two features are absent from the immature vertebral body.

Sensenig (1949) demonstrated that the vertebral body is formed by the fusion of the rostral and caudal halves of secondarily divided sclerotomes, with the interposition of vessels between these two halves. If these vessels, which are branches of the intersclerotomic arteries, are the equatorial arteries, then the plane of the equatorial arteries indicates the plane of original sclerotomic division. All the tissue lying between adjacent sets of equatorial arteries is thus derived from a single mesenchymal sclerotome (Fig. 14). The arteries of the upper metaphysis supply tissue derived from the caudal hemisclerotome and *vice versa*. The base of the neural arch lies cephalad to the segmental artery, and the ascending branch of the spinal artery may mark the place of original sclerotomic division on the dorsal surface of the vertebral body.

The base of the neural arch is supplied by branches from the upper metaphyseal anastomosis and from branches of the descending branch of the spinal artery within the spinal canal. This indicates that the base, at least, of the neural arch is derived from the caudal hemisclerotome. This deduction, based on arterial anatomy, confirms Sensenig's histological evidence that the majority of the cells giving rise to the neural process originated from the caudal hemisclerotome.

SUMMARY

The arterial anatomy of 60 lumbar and lower dorsal vertebral bodies from eight subjects aged between 29 weeks gestation and 15 years was studied. The arteries had been injected with a suspension of barium sulphate and the vertebrae decalcified, sectioned and radiographed.

In the specimen of 29 weeks gestation, the equatorial arteries were present. Precursors of the metaphyseal arteries lay obliquely over and completely outside the ossification centre. These precursors originated from an irregular network of perichondral arteries near the equator. By six months of age, the perichondral arteries had migrated discally and had become well organized metaphyseal anastomoses while the metaphyseal arteries had become horizontal. Also by six months, the extra-osseous longitudinal anastomoses had developed into the adult pattern. In the 36 weeks fetus, the ends of the unbranching metaphyseal arteries were incorporated into the ossification centre. This central relationship was maintained into adult life, but, as the ossification centre expanded, the branches of the intra-osseous arteries followed the zone of ossification in a centrifugal manner. In infancy, the metaphyseal arteries were approximately equal in length and the equatorial arteries divided in the middle of the vertebral body; by the age of 15 years, the metaphyseal arteries arising from the anterolateral surfaces were longer than those which arose from the posterior surface, and the equatorial arteries divided behind the mid-point. From these arterial observations, a number of deductions concerning the mode of growth of the vertebral body have been drawn.

Preterminal coils and typical peripheral arteries, frequent features in the adult vertebral body, were not seen in any of these specimens. There was no evidence of any epiphyseal growth plate, nor of epiphyseal arteries in these specimens.

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