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The human vertebral column at the end of the embryonic period proper

1. The column as a whole

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INTRODUCTION

The development of the human vertebral column during the embryonic period proper has been summarized recently (O'Rahilly & Meyer, 1979), and the fetal column has been re-studied by radiography (Bagnall, Harris & Jones, 1977*a*, *b*, 1979). Apart from the important work of Bardeen (1905*a*, *b*), however, scarcely any illustrations of either the cartilaginous column as a whole or of individual vertebrae are available. Hence the detailed structure of the embryonic column is ill-understood, which is all the more surprising in view of the frequency and importance of such anomalies as spina bifida.

The present study was undertaken (1) to provide a well illustrated account based on precise reconstructions at the important junction between the embryonic and fetal periods, (2) to assess the degree of variation found within a single developmental stage,* and (3) to examine closely the interrelationships between the developing vertebral column and the nervous system. It is proposed to publish detailed accounts of the regional subdivisions of the vertebral column in a further series of articles.

MATERIAL AND METHODS

Serial sections of nine embryos of stage 23, 8 post-ovulatory weeks (O'Rahilly, 1973), belonging to the Carnegie Collection were studied: 27 mm (Nos. 100, 5422, 7425 and D-122), 28 mm (No. 108), 20 mm (Nos. 75, 227 and 4525) and 31 mm (No. 9226) C–R. One series was sectioned coronally, another transversely, and the remainder sagittally. The stains included haematoxylin and eosin, alum cochineal and azan, and one specimen had been treated with silver. The thickness of the sections varied from 12–50 μm. Graphic reconstructions based on every second to every eighth section were prepared from each of the embryos.

The abbreviations C, T, L, S and Co (for cervical, thoracic, lumbar, sacral and coccygeal) will be followed, where appropriate, by either V for vertebra or N for nerve. Thus, TV6 signifies the sixth thoracic vertebra.

* Within the embryonic period proper, the Carnegie stage (O'Rahilly, 1979) should be cited if possible, in order to permit valid comparisons between embryos to be made. The term 'horizon' is obsolete, and Roman numerals have been discarded. If the stage is unknown, and in the case of all fetuses, the crown–rump length in millimetres should be provided. Each reader is thereby enabled to make an individual assessment of prenatal age.

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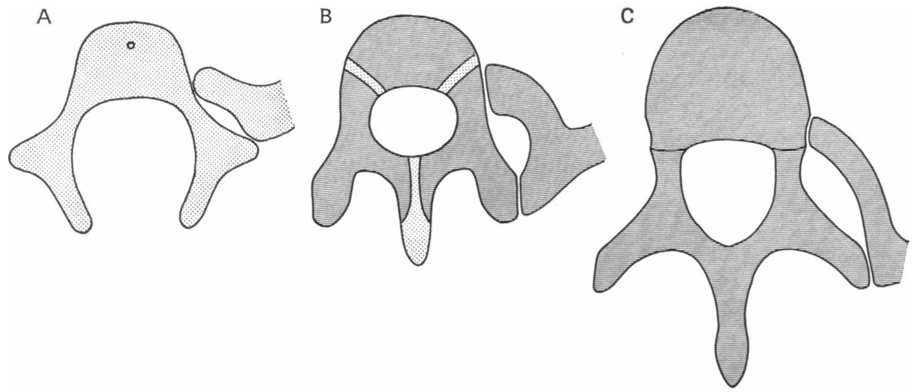

Fig. 1. Scheme to show a typical thoracic vertebra: (A) at the end of the embryonic period proper, (B) at birth, and (C) in the adult. (A) and (C) resemble each other in that the head of the rib articulates with a mass of cartilage that represents the future vertebral body in (A), and with the osseous vertebral body in (C). In (B), however, the presence of the neurocentral synchondrosis shows that the head of the rib articulates with the neural arch and not with the centrum.

The term 'centrum', introduced by Owen, needs some clarification. In the cartilaginous vertebral column, the centrum is the axially placed mass from which the neural processes emerge (Fig. 1 A). Because the centrum is directly continuous with the developing neural arch, some authors, e.g. Wyburn (1944), prefer to speak of the cartilaginous vertebral body, and to reserve the term centrum for the later appearing osseous mass that is separated from the osseous neural arch by the neurocentral synchondrosis (Fig. 1 B). The rib articulates with the neural arch only, not with the centrum (Fig. 1 B). In the adult (Fig. 1 C) the head of the rib articulates with that part of the body of the vertebra that has ossified from the neural arch.

RESULTS

In all the specimens studied the vertebral column was flexed into an almost continuous curve composed of the primary thoracic and sacrococcygeal curvatures. A slight flattening appeared to be present in the lumbosacral region but no indication of a secondary cervical curvature was seen.

Twelve pairs of cartilaginous ribs were clearly delineated (Fig. 2). The upper seven were anchored to the sternum, which (at 31 mm) was bipartite below the level of the third ribs. The scapula occupied a high position: CV4–TV4 in No. 5422, CV5–TV4/5 in No. 7425 (Fig. 2), and CV6–TV4 or 5 in No. 9226. The lower border of the cricoid cartilage varied in vertebral level from CV3/4 to CV4, and the tracheal bifurcation from TV2/3 to TV4.

The summit of the column was formed by the dens (Fig. 3), from which the notochord emerged to traverse the foramen magnum and enter the base of the skull (Müller & O'Rahilly, 1980). The dens consisted of an apical portion (which we have designated X) and a basal part (Y) in continuity with the centrum (Z) of the axis (Fig. 4).

The spinal cord, nerves and ganglia are shown in Figures 4 and 5.

The total length of the vertebral column measured along the notochord from the tip of the dens to that of the last coccygeal component was approximately 20–23 mm in

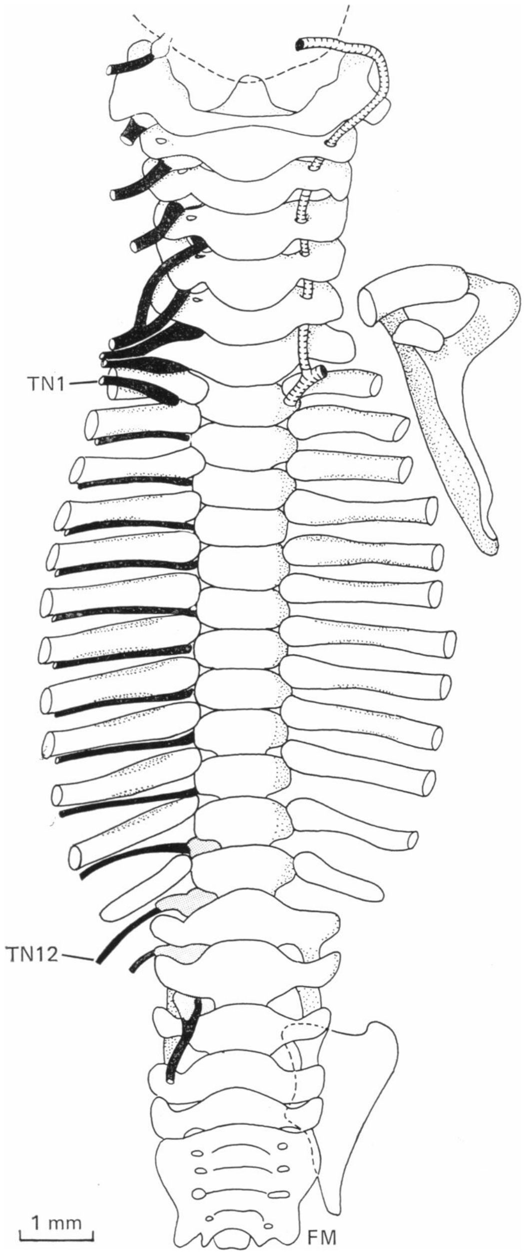

Fig. 2. Graphic reconstruction of vertebral column of a 27 mm embryo (No. 7425), seen from in front. On the left side of the body, the vertebral artery, the scapula and the lateral end of the clavicle, and the future hip bone are shown. On the right side, the spinal nerves from CN1 to SN2 are included. The transverse processes of the vertebrae have been omitted. The interrupted line above represents the foramen magnum. In Figures 2–5, the bar represents 1 mm.

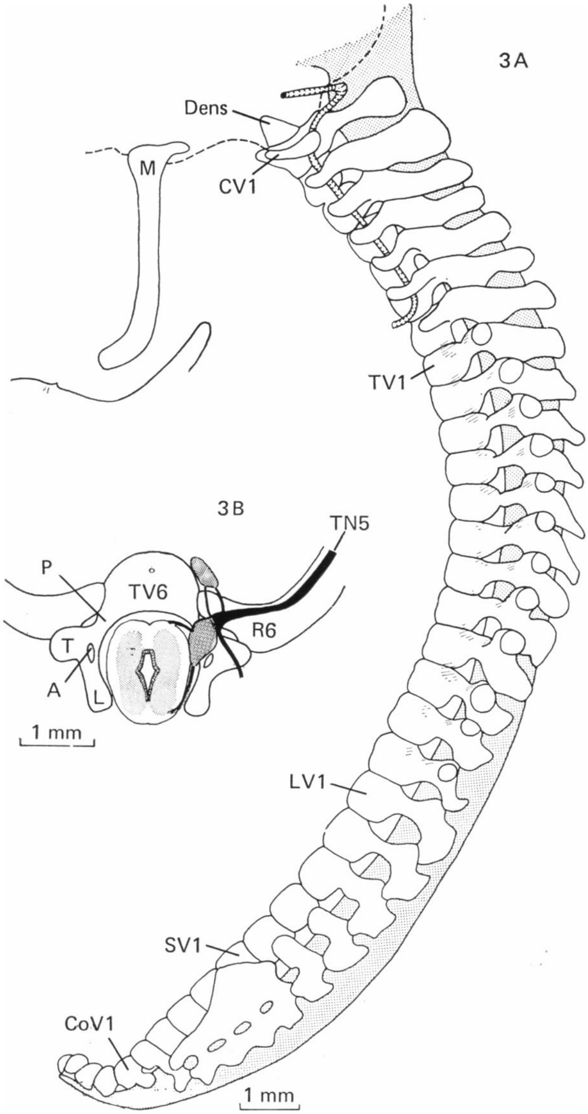

Fig. 3. (A) Graphic reconstruction of vertebral column and spinal cord (shaded) of a 27 mm embryo (No. 5422), left lateral aspect. The cartilage (Meckel's) of the first pharyngeal arch (M) and the vertebral artery are included. The areas for articulation with the ribs are shown by parallel lines. The transverse processes (of thoracic vertebrae only) appear as circular outlines. The cartilaginous bars that extend dorsally are the laminae. (Spinous processes are not yet present.) The interrupted line represents the skull.

(B) Graphic reconstruction of the sixth thoracic vertebra and sixth ribs of a 31 mm embryo (No. 9226), from above. Although the ribs appear to articulate with the centrum, these parts of the vertebra are believed to be portions of the neural arches. The site of the notochord is indicated in the centrum. The unfused neural arches consist of pedicles (P), transverse (T) and articular (A) processes, and laminae (L). The transverse section of the spinal cord shows germinal (ventricular), mantle (intermediate), and marginal layers. The dorsal and ventral roots of the fifth thoracic nerve lead to the spinal ganglion, on the lateral side of which the dorsal and ventral (intercostal) rami can be seen. Two rami communicantes to the sympathetic ganglion are visible.

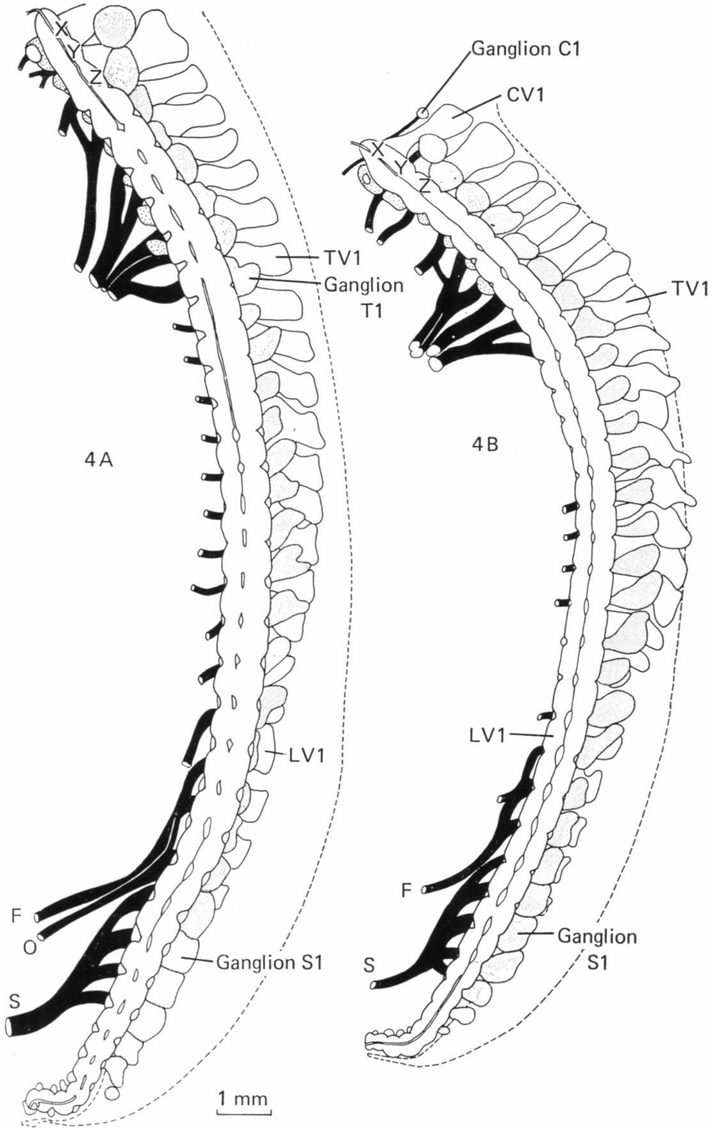

Fig. 4. (A) Graphic reconstruction of a median section of the vertebral column of a 30 mm embryo (No. 75). The spinal nerves fron CN1 to SN3, the spinal ganglia (C2 to Co1), and the neural arches from CV1 to LV4 of the right hand half of the body have been added. The course of the notochord from the dens to the coccyx is clearly visible. The interrupted line indicates the dorsal limit and the tip of the spinal cord. F, Femoral nerve; O, obturator nerve; S, sciatic nerve; X, tip of dens; Y, base of dens; Z, centrum of axis. (B) Similar view from a 27 mm embryo (No. 5422).

fixed, sectioned, reconstructed embryos. Hence the column is about two thirds of the C–R length. The widest vertebra was the atlas and, from the cervicothoracic junction downwards, the transverse diameters of the vertebrae gradually narrowed. The degree of union of the sacral vertebrae varied. Four to six coccygeal elements were present.

The proportions of the regional subdivisions of the column are illustrated in

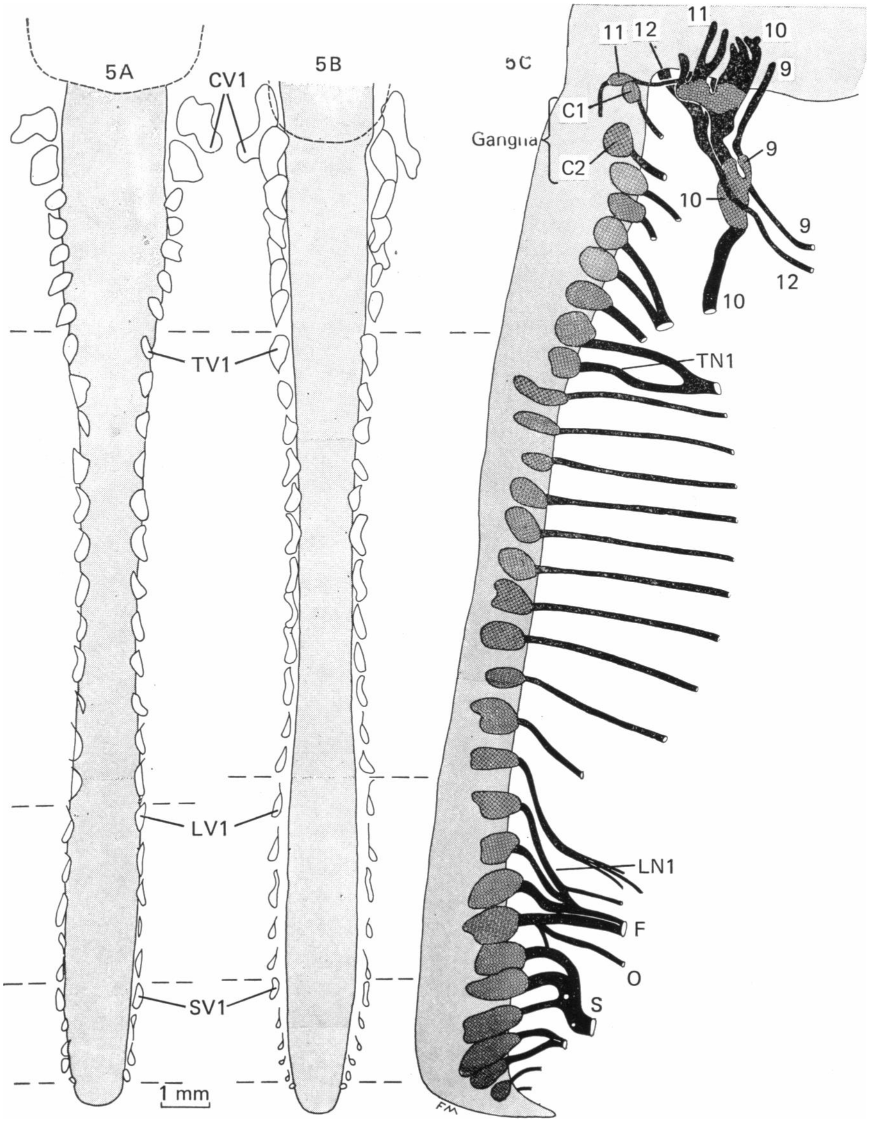

Fig. 5. (A–B) Graphic reconstructions of the tips of the unfused neural arches and the spinal cord (shaded) of 31 mm (No. 9226) and 27 mm (No. D-122) embryos, seen from behind. Cervical and lumbar enlargements of the spinal cord are identifiable. The interrupted lines above represent the foramen magnum. The horizontal lines are placed between the various vertebral regions. (C) Graphic reconstruction of the spinal cord (shaded), spinal ganglia (shaded more darkly), and spinal nerves (CN1 to CoN1) of a 27 mm embryo (No. D-122), right lateral aspect. Cranial nerves 9 to 12 and cranial ganglia 9 to 11 are included. F, Femoral nerve; O, obturator nerve; S, sciatic nerve.

Figure 6, which is based on the six sagittally sectioned specimens. The mean values are CV, 24 %; TV, 37·5 %; LV, 18 %; SV, 14·5 %; and CoV, 6 %.

The appearance of a typical vertebra (TV6) is shown in Figure 3B. It consisted of a continuous mass of cartilage formed by the centrum (in which the notochord was visible) and two neural processes. The tips of the neural processes were beginning to turn medially, although the extent of the spinal cord that was covered by the develop-

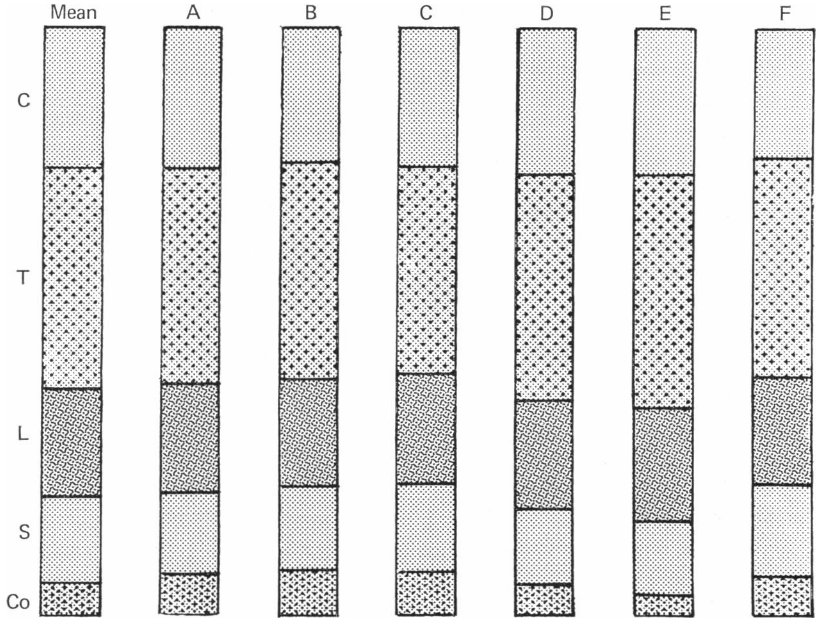

Fig. 6. The relative proportions of the regional subdivisions of the vertebral column in six embryos of stage 23. The first column shows the mean values. The thoracic component is the longest, followed by the cervical, lumbar, sacral, and coccygeal. In subsequent development the cervical region tends to decrease whereas the lumbar component increases. (A) No. 5422, 27 mm; (B) No. 75, 30 mm; (C) No. 4525, 30 mm; (D) No. 227, 30 mm; (E) No. 100, 27 mm; (F) No. 108, 28 mm.

ing neural arch was variable (Figs. 3, 4). Each neural process comprised a pedicle, two articular processes, a transverse process and a lamina. The laminae did not meet each other and a spinous process was not yet present. The laminae were joined together by collagenous fibres, the deepest layer of which was the membrana reuniens dorsalis. The neural (future vertebral) foramen, incomplete dorsally, was occupied almost entirely by the spinal cord. The future facets for the ribs were seen (Fig. 3A): one on the future body and another on either the pedicle or the front of the transverse process for the corresponding rib, and a third area on the future body for the subjacent rib. Intervertebral foramina were evident (Fig. 3A) and were occupied by the spinal ganglia (Fig. 5C).

The intervertebral discs were evident peripherally as the anuli fibrosi but the perinotochordal area consisted of special embryonic cells that connected the vertebrae so as to form a continuous cellular column. Enlargements of the notochord (Fig. 4) represented the prenatal nuclei pulposi. Each disc was broad at its periphery and thin centrally. The discs were thicker in the lumbar than in the cervical and thoracic regions.

The relative anteroposterior position of the notochord varied from one region to another (Fig. 7). It was mostly in the anterior half of the centra (Fig. 4), especially in the thoracic region, but it might enter the posterior half in the lumbosacral region. Notochordal flexures were not observed.

The spinal cord showed cervical and lumbar enlargements (Fig. 5A, B), which were associated, as in the adult, with the emergence of the large nerves to the limbs (Fig. 5C). The maximum circumference of the cervical enlargement was approximately at the level of CV5, which was little different from the condition in the adult. The maxi-

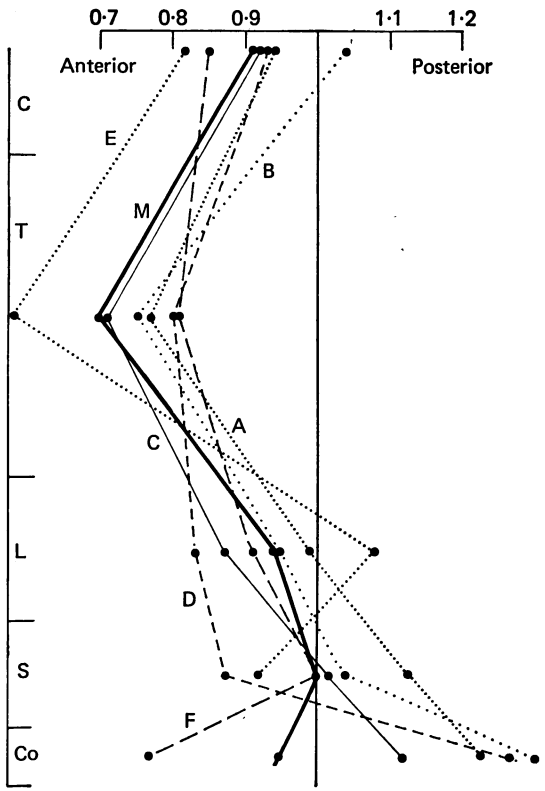

Fig. 7. Scheme to show the relative anteroposterior position of the notochord in six embryos of stage 23 in relation to a central axis (vertical line) through the centra. The distance of the notochord to (*a*) the anterior and (*b*) the posterior border of the centrum was measured for each vertebra. The ratio a/p was then established, and finally the mean ratio for each subdivision (e.g. cervical) was calculated for each of the six embryos. Although the notochord is mostly in the anterior half of the centra, especially in the thoracic vertebrae, it varies according to region and may enter the posterior half in the lumbosacral area. (A) No. 5422, 27 mm; (B) No. 75, 30 mm; (C) No. 4525, 30 mm; (D) No. 227, 30 mm; (E) No. 100, 27 mm; (F) No. 108, 28 mm; M, the mean.

mum circumference of the lumbar enlargement, however, was at about LV3, which is several vertebral segments lower than in the adult.

Because all the embryos examined belonged to the same morphological stage of development (O'Rahilly, 1973), it was possible to assess the degree of variation. The chief variations found were the number of coccygeal elements, the degree of union of the sacral vertebrae, the extent of dorsal growth of the neural processes, the anteroposterior position of the notochord, the inclusion or exclusion of CV7 in the articulation of the first rib, and the degree of completion of the foramina transversaria in the cervical region.

DISCUSSION

Brockmann (1942) claimed that, up to about 25 mm, two types of embryos are found: (1) in which the vertebral column forms a smooth curve, and (2) in which a slight lordosis appears. His involved study would need to be confirmed. The secondary cervical curvature begins early, at least by '9½ weeks (conceptual age)' according to Bagnall *et al.* (1977*a*). It is not visible in the present series but an indication can be seen at least by 69 mm (O'Rahilly & Meyer, 1956, Fig. 3).

The length of the column found here (20–23 mm) is in agreement with the data of Jackson (1909), from whose Table 1 (p. 366) it appears that the column remains approximately two thirds of the C–R length from about 6–7 post-ovulatory weeks to the end of fetal life. The gradual decrease in transverse diameter of the column from the cervicothoracic junction downwards is not marked by an accentuated constriction such as has been illustrated at the lower thoracic or thoracicolumbar area during the fetal period (and in the adult) by Jonata (1938, Fig. 41).

From data presented by Bardeen (1905*a*, *b*) it can be deduced that fusion of the sacral vertebrae begins during stage 18, and that all five sacral elements are involved in the process by about stage 21. In 19 Carnegie embryos studied by Bardeen (1904), the stages of which are now known, the number of coccygeal vertebrae (from stage 18 to stage 23) varied from four to eight. At stage 23 he found either five or six. The sagittally sectioned embryos examined here possessed 33–35 vertebrae, depending on the presence of four to six coccygeal elements. As Bardeen (1908–9) pointed out, "regional variation in the embryonic vertebral column corresponds approximately with that in the adult".

The proportions of the regional subdivisions (Fig. 6) given here agree well with the figures listed by Jackson (1909), from whose Table 1 it appears that the cervical region later tends to decrease, the lumbar component to increase, and the other regions to remain approximately the same. Proportions at stage 23 are also given by Friedland & de Vries (1975). Further details relating to longitudinal growth have been published recently by Bagnall *et al.* (1979).

The relative anteroposterior position of the notochord presumably depends on the relative growth of the ventral and dorsal portions of the column in any given region. There appears to be a tendency towards more rapid ventral growth, and the "alteration in position of the site of the foetal and adult nucleus pulposus within the disc may be due to the growth in girth of the discs and vertebrae being greater at the ventral surface" (Peacock, 1951). Furthermore, in persistent notochordal tracks in three full term fetuses and an infant, the notochordal segment "was predominantly posterior in both thoracic and lumbar intervertebral discs in all four cases" (Taylor, 1972).

By 29 mm, the peripheral portion of the intervertebral disc may "be truly termed the annulus fibrosus" (Peacock, 1951). The special mesenchyme of the perinotochordal area, which perhaps "may appropriately be termed precartilage", gives an 'erroneous' impression "that the vertebral column forms a continuous cartilaginous column at this stage" (Walmsley, 1953). The complicated modifications of the notochord, whereby the prenatal nucleus pulposus is produced, have been described by Peacock (1951), according to whom the specialized tissue of the perinotochordal area "later differentiates to form the fibro-cartilaginous component of the disc, and is a potential source of additions for the growth of the nucleus pulposus of post-natal life".

The spinal cord ends in the coccygeal region. During early fetal life the conus medullaris terminates successively at sacral and lumbar levels. By the middle of prenatal life, the conus has reached the level of LV4 (Barry, 1956); by birth, LV2 or 3; and "the 'adult' level about 2 months after term" (Barson, 1970*a*). As a result, the lumbar enlargement and the attachment of the large nerves destined for the lower limb undergo a relative rostral shift.

Prevention of further closure of the neural arches would lead to a dysraphic condition characterized by a "pedicular and laminar splaying", which is "the fundamental bony defect of spina bifida" (Barson, 1970). Indeed the posterior view of the column at stage 23 (Fig. 5A, B) bears a striking resemblance to a total rachischisis (Cf. Barson, 1970*b*, Fig. 10).

The high position of the scapulae is of clinical interest. Normally they descend relatively in fetal and early postnatal life. Persistence of a high position is a major component of Sprengel's deformity.

Several noteworthy features are not found until the fetal period. The right and left laminae fuse, by 50 mm in the mid-thoracic region (Bardeen, 1910). Calcification begins in the neural arches and centra, by about 54 mm in the mid-thoracic region (O'Rahilly & Meyer, 1956) or even as early as 40 mm (Noback & Robertson, 1951), and ossific centres are well defined in some centra by 60 mm (Peacock, 1951). A number of articular cavities appear early in the fetal period (Töndury, 1958), including that of the sacro-iliac joint (Schunke, 1938). Although the position of the zygapophysial joints is fixed as early as 26 mm, the inclinations of the articular facets alter during fetal life and during childhood (Huson, 1967).

SUMMARY

The present investigation of the vertebral column at 8 post-ovulatory weeks, the first such study based on precise reconstructions, has revealed 33 or 34 cartilaginous vertebrae arranged in flexion and approximately 20–33 mm in total length.

At the end of the embryonic period proper, a typical vertebra, such as TV6, consists of a centrum that is continuous with two neural processes. Pedicles, articular and transverse processes, but no spinous processes, are identifiable. The tips of the neural processes, which are formed by the laminae, are connected by fibrous tissue and resemble the condition of total rachischisis.

The union of the laminae, the onset of ossification, and the appearance of articular cavities are characteristic of the early fetal period.

The variations encountered within a single developmental stage were noted. They were mostly minor, e.g. the number of coccygeal elements and the extent of the dorsal growth of the neural processes.

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