Vertebral Column Development and Its Relation to Adult Pathology

Normal notochordal and vascular attrition leaves weak spots in intervertebral discs through which intravertebral prolapse of disc material frequently occurs. Some varieties of prolapse cause somatic spinal pain. Asymmetrical and asynchronous growth of normal vertebral arches rotates thoracic vertebral bodies slightly to the left in infants and to the right in adolescents. Primary vascular asymmetry could cause the observed vertebral asymmetry.

Luschka's joints develop in the cervical spine during childhood and give some protection against postero-lateral disc prolapse, but cervical zygapophyseal joints give little protection to the disc in sagittal plane movements. The lumbar zygapophyseal joint plane changes from a coronal orientation in infants to a biplanar coronal and sagittal orientation in adults, which enables the joints to restrain both rotation and excessive flexion. This explains the observed pattern of stress related age changes in the joints.

Development and growth have an important bearing on adult structure and there are many areas where a knowledge of development is essential to a proper understanding of normal variation and adult pathology. Three important topics linking vertebral column development to normal variation and pathology in adults will be described:

1. Schmorl's nodes and their aetiology.
2. Scoliosis and its developmental basis.
3. Development of cervical and lumbar spinal synovial joints in relation to adult pathology.

Schmorl's Nodes

In the human embryo, three axial structures influence vertebral column developments: the notochord, which induces mesenchymal vertebral column formation around it; the neural tube, which controls growth of the neural processes which will form the vertebral arches; the dorsal aorta and its intersegmental branches, which play a role in vertebral column segmentation (Tanaka and Ulthoff 1981, Taylor and Twomey 1984a).

The notochord forms the original nucleus pulposus of the intervertebral disc, but notochordal cells gradually disappear from the intervertebral disc during the first postnatal decade. In the normal young disc, the nucleus is a viscous fluid contained within an elliptical spherical envelope formed by the anulus fibrosus and cartilage plates (Figure 1A). The nucleus never has any blood vessels or nerves within it, but during fetal life, the anulus and cartilage plates are well vascularized from the intersegmental vessels. These vessels gradually involute during the first ten to fifteen years of postnatal life.

The conversion of the cylindrical embryonic notochord to a series of segments forming the nucleus pulposus of fetal and infant intervertebral discs, leaves central weak spots in the cartilage plates which form the upper and lower boundaries of each nucleus (Figure 1A). These weak spots persist in children and adolescents in the form of 'dimples' in the centre of the nuclear aspect of each cartilage plate (Bohmig 1930, Taylor 1973). Experimental compression testing of two vertebral bodies and the intervening disc show that these central dimples...
Vertebral Column Development

Vascular arcades develop in fetal cartilage plates, originating from the peripherally situated intersegmental vessels and radially directed towards the rapidly growing nucleus pulposus (Figure 1B). They persist into infancy and childhood, and as they involute, they leave radial grooves in the growing centrum. As they disappear, the vessels are replaced by connective tissues, less strong than the surrounding cartilage, constituting channels from near the nucleus pulposus to the periphery of the centrum. These channels pass between the ring apophyses and the centrum or into the peripheral spongiosa of the centrum, and the compressed disc may rupture along them in adolescents or young adults (Taylor and Twomey 1984a).

These areas of reduced resistance explain the two varieties of Schmorl's nodes or intravertebral disc prolapses seen in adults (Figure 2). Schmorl described intravertebral prolapses of nuclear material in thirty-eight per cent of 10,000 hemisectioned spines — in a survey so massive that it is unlikely ever to be reproduced. These prolapses most commonly form multiple aligned central nodes along the line of the original notochord, but occasionally peripherally located nodes are seen in the situation of the former radially directed vessels to the anterior aspect of the vertebra (Bohmig 1930, Schmorl and Junghanns 1971). The nodes are usually found in lower thoracic or lumbar vertebrae. Studies of age-related incidence show that Schmorl's nodes are as common in adolescents and young adults as in the elderly, supporting the view of their developmentally conditioned origin (Taylor and Twomey 1984a).

It is impossible to be certain whether the more common variety cause pain, but it seems unlikely that they are a significant cause of pain or dysfunction. Surgical experience suggests that cancellous bone is relatively insensitive to painful stimuli; the nerves in bone marrow are mainly unmyelinated and probably concerned with the regulation of blood flow (Sherman 1963). Estimates of Schmorl's node volume suggest that it is usually less than 2 per cent of disc volume; they would not occasion any measurable reduction in disc height (Twomey and Taylor 1984).

On the other hand, the less common anterior prolapses (found in 5% of post-mortem material) are often considerably larger in volume than central nodes, and it is feasible that they may cause acute local ('somatic') pain by stimulating nociceptive endings in the peristeum or anterior longitudinal ligament. Anterior prolapses may be traumatic in origin, tend to occur in young adults, and are described on X-rays as a 'limbus vertebra' since the protruding material separates the annular apophyseal ring from the centrum (Taylor and Twomey 1984a).

Similar anterior prolapses are a prominent feature of Scheuermann's kyphosis when they are accompanied by a more generalized irregularity of the vertebral end plates with many small Schmorl's nodes. These features lead to shortening of the anterior spinal elements with resulting kyphosis (Schmorl and Junghanns 1971).

Developmental Skeletal Asymmetry

The topic of scoliosis can be approached from the perspective of developmental asymmetry. A variety of developmental asymmetries have been described and family studies show a strong genetic influence in both scoliosis and limb length asymmetry (Taylor and Singer 1980, Taylor et al 1982). A study of the literature and personal observation suggest that primary vascular asymmetry and cerebral dominance are important determinants of skeletal asymmetry, vascular factors being more important in spinal asymmetry (Taylor and Twomey 1984) and cerebral dominance in limb asymmetry (Morgan and Corbalis 1978).

Asymmetry of vertebral arch development in fetuses and infants is characterized by a tendency for right arch ossification to begin before left arch ossification, the right arch being subsequently larger than the left (Taylor 1983a). This tends to rotate the anterior elements away from the larger side of the arch, which has a longer
Vertebral Column Development

The descending aorta lies on the left side of vertebral bodies from T5 to T9 or T10, becoming anterior in position by T12, before deviating slightly to the left again anterior to mid lumbar vertebrae. Its asymmetrical influence on growth differs in thoracic and lumbar regions, due to the difference in shape of thoracic and lumbar vertebral bodies (Figure 5). The influence on thoracic vertebral growth is seen in an asymmetrical flattening of these vertebral bodies at the area of contact. This asymmetry is not visible in infancy, appears during later childhood and is most common in adult vertebrae (Taylor 1983a).

The pulsatile pressure of the aorta is probably also responsible for the asynchrony observed in neurocentral fusion, right thoracic neurocentral growth plates fusing before the corresponding growth plates on the left. This reverses the direction of rotation of the anterior elements and from the age of about seven years, vertebral bodies tend to be twisted to the right, in association with longer left pedicles (Figure 3). In contrast, the asymmetry of oxygenation in the fetal aorta distal to the entry of the ductus arteriosus. It is suggested that better oxygenated blood would reach the right arches than would reach the left arches, from about T4 down to T10 (Figure 4). The right arches in this region are ahead of the corresponding left arches in their development, as attested by earlier appearance of their primary centres of ossification.

This difference would tend to gradually disappear postnataally. However, asynchrony in growth and maturation and asymmetry in vertebral arch size persist during childhood and adolescence. The direction of vertebral body rotation changes by about seven years, as a further vascular influence has its effect. The descending aorta lies on the left side of vertebral bodies from T5 to T9 or T10, becoming anterior in position by T12, before deviating slightly to the left again anterior to mid lumbar vertebrae. Its asymmetrical influence on growth differs in thoracic and lumbar regions, due to the difference in shape of thoracic and lumbar vertebral bodies (Figure 5).
Vertebral Column Development

The position of the lumbar descending aorta, with the greater transverse diameter of lumbar vertebral bodies, may favour rotation of mid-lumbar vertebral bodies to the left (Figure 5).

Scoliosis screening surveys confirm that minor forms of rib hump (usually on the right) or lumbar hump (usually on the left) are clinically detectable by the trained observer in up to 20 per cent of adolescents (Taylor 1983b). The vast majority of these will never progress to serious deformity, but the position and pattern of the rotational deformity is similar to that of progressive severe scoliosis. This suggests that the latter is superimposed on the 'physiological scoliosis' which is common in adolescents and almost universal in adults (Taylor et al 1980).

It is the causes of progression of scoliosis which now require elucidation, and until that problem is solved, all minor curves with rib humps measuring more than 5 degrees with Bunnell's scoliometer (Bunnell and Cady 1982), or showing Cobb angles greater than 10 degrees, who have more than a year's growth remaining, should be regularly followed up until maturity. If the angle of curvature progresses beyond 25 degrees before skeletal maturity is reached, the patient may require brace treatment to prevent serious deformity.

One factor contributing to a greater likelihood of progression is the more slender vertebral body shape in females compared to males. The difference in vertebral shape appears from eight years onwards, and becomes more marked with growth during adolescence (Figure 6). This is due to greater growth in vertebral height in females and greater growth in vertebral girth in males. The greater growth in vertebral girth in males may be related to the effects of testosterone, from the enlarging testes, which produces more muscle in males, each fibre being stronger, the greater bulk and strength of muscle favouring the increased horizontal vertebral growth. During the period from 8 to 13 years the average female spine grows in length more rapidly than the male spine (Taylor and Singer 1980). Thus the female spine is more slender and has less strong muscle support than the male, so that if it has a slight twist and lateral curvature it is more likely to buckle under axial loading (Taylor and Twomey 1984b).

Postnatal Developmental Changes in Spinal Joints

The development of Luschka's joints in the cervical spine, and growth changes in the lumbar zygapophyseal joints both affect the patterns of adult pathology in these regions.

Luschka's Joints

In contrast to zygapophyseal joints, these are not true synovial joints but rather adventitious joints, which develop when the uncinate processes of the vertebra below grow long enough to come into contact with the inferior lateral margins of the vertebra above by about nine years (Tondury 1953, Orofino et al 1960, Hirsch et al 1967, Hirsch 1972, Tondury 1972). In this respect they may be considered analogous to the 'joints' between 'kissing spines' in an older age group where a bursa-like cavity develops between lumbar spinous processes which rub against one another.

Each uncinate process forming a joint with the vertebra above separates the nerve in the intervertebral canal from the intervertebral disc, whose transverse extent is less than that of the vertebrae bounding it. Thus, the nerve leaving the spinal canal runs laterally between two synovial joints. In contrast to the lumbar region, postero-lateral prolapse of cervical discs into the intervertebral foramen is rare and most cervical radicular compression is related to osteophytes from the zygaphophyseal joint or from Luschka's joint (Palms et al 1954, Epstein et al 1978).

Lower cervical discs receive good biomechanical support in the coronal plane from the widely spaced zygapophyseal joints, but in the sagittal plane, disc dimensions are small and they receive less effective support from the zygapophyseal joints. The latter are oriented at about 45 degrees to the coronal plane and would favour both rotation and translation in the sagittal plane. In addition, with the tendency to increasing cervical lordosis as a response to the thoracic kyphosis of ageing, considerable stress is placed on the posterior annulus. Thus, degenerative posterior bulging of intervertebral discs with associated osteophytes forms a 'transverse bar'. Sagittal movements of the cervical spine may repeatedly draw the spinal cord over this transverse bar, leading to the development of myelopathy (MacNab 1975). Alternatively or additionally, the transverse bar can irritate nerve roots approaching the intervertebral canals or the anterior dura of the spinal cord, causing radicular paraesthesiae and dural pain.

Lumbar Zygapophyseal Joints

The pattern of postnatal growth in lumbar zygapophyseal joints leads to a change in their shape and influences their functions and reaction to stress in the adolescent and adult. These joints are the most important restraining and guiding influence in lumbar
The fetal and infant lumbar zygapophyseal joint planes resemble those in the thoracic region in being approximately coronally oriented (Reschmann 1971). During childhood, the lumbar joint facets increase dramatically in size. Vertical growth occurs at the tips of the articular processes, such that the articular surfaces are in a vertical plane, in contrast to thoracic and cervical facets. Horizontal growth of the lumbar articular processes is in a posterior direction from their lateral margins. This forms a biplanar joint, which is coronally oriented anteromedially and sagittally oriented posterolaterally. When seen in horizontal section the adult joint outline resembles a boomerang (Figure 7).

The sagittally oriented posterior part of the joint resists rotational movements of the lumbar spine. Lumbar spinal movements in the sagittal plane were studied by Twomey and Taylor (1983) who found that flexion involved both forward rotation and forward translation of the upper vertebra upon the lower vertebra, flexion being resisted and brought to a halt by a buildup of resistance to forward translation in the coronal part of the zygapophyseal joint. The pattern of subchondral bone developed in the articular facets of adolescents and young adults, and the patterns of articular cartilage fibrillation seen in young adults and early middle age, both reflect the particular pressure stress on the coronally oriented parts of the joint (Figure 7).

Preliminary observations and measurements of subchondral bone thickness and articular cartilage in 50 lumbar spines of children and adults have shown that in both articular processes, subchondral bone thickening takes place with growth to maturity. This thickening is selectively much greater in the coronal part of the joint and in the superior articular processes in particular. The articular cartilage also shows earlier fibrillation and more severe vertical fibrillation changes in the coronal part of the superior facet compared to other parts of the joint (Figure 7). This relationship between the coronally oriented parts of the joint facets and pressure stress induced pathology, emphasizes the importance of avoiding excessive loading of the spine in the fully flexed position. The resistance to lumbar rotation offered by the sagittally oriented parts of the joint facets, is not associated with subchondral bone thickening in these parts of the joint, suggesting that the joint loading involved in rotation is much less than in flexion. Articular cartilage changes here appear to relate to shearing forces transmitted from the capsular attachments of the articular cartilage and multifidus insertions into the capsule. Tone in the multifidus may be essential to normal apposition of the posterior parts of the articular surfaces, since horizontal sections frequently show apposed surfaces anteriorly close to the ligamentum flavum, and separated surfaces posteriorly where the capsule is relatively slack. In younger joints, capsular fibres are frequently continuous with the posterior margin of the articular cartilage of the superior articular facet, while muscle insertions are partly into the capsule and partly into the posterior margin of the superior articular process of the vertebra below. Appearances in some older joints suggest that some joint meniscoid inclusions arising from the capsule are created by tearing or shearing off, of part of the posterior articular cartilage. Such capsular inclusions increase in frequency with maturation and ageing and are quite distinct from the synovial, fat-filled inclusions from the superior and inferior joint recesses.

Further measurement studies presently being carried out at the University of Western Australia and at the Western Australian Institute of Technology will relate patterns of stress with developmental and degenerative
Age changes in zygapophyseal joints, using a large series of about two hundred lumbar spines.

Acknowledgement

The authors wish to acknowledge the financial assistance of TVW Teledphon in work leading to the publication of this article.

References

Bohmg R (1930), The blood vessels and chord segments of the developing intervertebral disc their importance in disc degeneration, *Archives fur klinische Chirurgie*, 158, 374-424


Machnöb I (1975), Cervical spondylosis, Clinical Orthopaedics and Related Research, 109, 69-77


