PROGRESSION IN IDIOPATHIC SCOLIOSIS*

A PRELIMINARY REPORT OF A POSSIBLE MECHANISM

G. C. LLOYD-ROBERTS, JOHN R. PINCOTT, PETER McMENIMAN, I. J. L. BAYLEY, BRIAN KENDALL

From The Hospital for Sick Children, Great Ormond Street, London

Recent surveys have shown that idiopathic structural scoliosis of mild degree is generally not progressive. We will propose a mechanism which may be responsible for deterioration in the few. It has been observed that the spinal cord, although displaced towards the concavity, does not rotate in company with the vertebrae, thus exposing the emerging nerve roots to the effects of traction and possibly of entrapment. We suggest that progression occurs when the neuraxis is unable to adjust to the change in the anatomy of vertebral column. Our proposition is based upon our findings in a complete spinal column obtained from a baby with structural scoliosis. Support is provided by intercostal angiography, and by observations upon normal anatomy, the pathological anatomy of mature scoliotic spines and the anatomy of contrived scoliosis in normal spines. Although our histological and electrophysiological investigations are incomplete we can demonstrate a significant increase in degenerate cells in the dorsal root ganglia at the apex on the convex side. Lack of suitable necropsy material prevents us from confirming our observations so that our report is inevitably preliminary. We enter a plea that careful examination of the neuraxis be undertaken whenever a specimen of a scoliotic spine becomes available.

Our understanding of the nature of idiopathic scoliosis is limited by our failure to identify two essential features. We do not know why the deformity occurs in the first place nor do we understand the mechanism of progression in its initial stages. We are concerned only with the second uncertainty and in particular with that phase of evolution between the onset and the stage at which we may reasonably suppose that compression and distraction forces react upon the growth plates of the vertebral column. Once this is established progression is both intrinsic and autonomous.

It is becoming increasingly evident that idiopathic structural scoliosis, mild in degree, with little if any tendency to deteriorate, is not uncommonly found among the general population specifically screened for this purpose. Rogala and Drummond (1977) have undertaken a prospective study of idiopathic scoliosis in children between twelve and fourteen years of age, of whom 14 902 were followed for two years. At the first examination 603 were found to have structural curves, giving an incidence of 4 per cent; approximately one third of these measured more than 10 degrees. During the two years forty-one developed curves which required treatment. This represents 0.27 per cent of the patients screened and 6.8 per cent of those with

identifiable scoliosis. The remainder either resolved or remained static. The dilemma posed by this recent knowledge requires that we identify those factors that determine progression in those children who deteriorate. Herein lies an essential feature of the clinical problem, for whether or not we discover at some time in the future the primary cause of these curves, we now know that relatively few of them will warrant the services of orthopaedic surgeons.

In attempting to explain the mechanism by which deterioration is initiated we will propose that there is interference with the normal axonal transmission of the nervous impulse on the convex side. We will suggest that anatomical derangement within the spinal column modifies the course of the nerves as they emerge from the spinal canal, thus exposing them to the effects of traction and possibly of compression.

We will in this preliminary report restrict ourselves largely to a description of the structural changes found in one specimen obtained at necropsy from a baby with severe idiopathic structural scoliosis, and discuss certain features of normal and pathological anatomy relevant to our hypothesis. We will briefly consider certain histological and electromyographic features, but intend to report upon these in greater detail in the future.

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G. C. Lloyd-Roberts, M.Chir., F.R.C.S., Orthopaedic Surgeon, The Hospital for Sick Children, Great Ormond Street, London WC1N 3JH, England.

John R. Pincott, M.B., B.S., M.R.C.Path., Senior Lecturer in Histopathology at the Institute of Child Health, Guilford Street, London WC1N 1EH, England.

Peter McMeniman, F.R.C.S., 386 Ferguson Road, Norman Park, Brisbane, Australia.

I. J. L. Bayley, F.R.C.S., Senior Registrar, Royal National Orthopaedic Hospital, 234 Great Portland Street, London W1N 6AD, England.

Brian Kendall, F.R.C.P., F.F.R., D.M.R.D., Consultant Neuroradiologist, The Hospital for Sick Children, Great Ormond Street, London WC1N 3JH, England.

Fig. 1

Fig. 2

Figure 1—Scoliosis with cutaneous neurofibromatosis without a local spinal lesion. The myelograph shows that the spinal cord is displaced towards the concave side of both primary and secondary curves. Figure 2—Intercostal angiograph. The anterior spinal artery is clearly seen lying in the position of the midline of the cord. The artery would be displaced towards the convex side if the cord had rotated.

THE BACKGROUND

Interest in the association between both hypoplasia of the lung and some varieties of congenital heart disease and idiopathic scoliosis led us to investigate the circulation patterns of scoliotic spines by intercostal angiography. We were seeking for some variation from normal which might explain these associations. These investigations, though unrewarding in their purpose, stimulated a study of the relevant literature, and in particular the contribution of Hilal and Keim (1972). These authors observed without further comment that the anterior spinal artery, although displaced towards the concave side, did not appear to rotate in company with the vertebral bodies. Re-examination of our material confirmed this observation (Figs. 1 and 2). Two questions were inevitably posed. First, does the position of the anterior spinal artery faithfully reflect the orientation of the spinal cord? Secondly, if the cord does not rotate to a degree which corresponds to that of the vertebral column, could this in any way contribute towards the evolution of a progressive curve?

It was clearly necessary that we next study the normal anatomy of the spinal cord and its immediate neighbours in order to establish whether the cord was in fact capable of resisting a rotational force.

Figure 3—The normal spinal canal exposed from the back. Note the emerging nerve roots. (By kind permission of The Museum of The Royal College of Surgeons of England.)

Fig. 3

NORMAL ANATOMY RELATIVE TO THE STUDY

The structures with which we are concerned are the spinal cord, the emerging nerve roots, the meninges, especially the dura mater with its associated nerve root sleeves and denticulate ligaments, and finally the skeletal components of the column. Figure 3 shows the spinal cord and its immediate relations exposed from behind, and illustrates some of the structures considered. The spinal cord occupies a midline position and the dura mater, securely attached above to the foramen magnum, extends to surround the emerging nerves and becomes incorporated with their outer sheaths. The nerves with their dural connections run an oblique course towards the intervertebral foramina, thus acting as guy-ropes which may inhibit free rotary movement of the cord and its coverings in the area of vertebral rotation, especially if the vertebral bodies above and below do not rotate. Furthermore, the dura mater is a tough unyielding structure which may, because of this property, itself resist a torsional strain and so prevent its transmission to the spinal cord. In this connection, however, the denticulate ligaments may be of prime importance. Their fish-tail attachments suggest that they have evolved as stabilisers of the spinal cord in its

relationship to the dura mater. Their strength is harnessed by neurosurgeons to rotate the cord for the purpose of performing anterior cordotomy. The corollary is that they may oppose a rotation strain imposed upon the cord by the vertebral deformity if the dura does not rotate to a corresponding degree.

Additional stabilisation of the cord is possibly provided by continuity with the brain stem above and the filum terminale below—to which the dura is also attached. Furthermore, the attachment of dorsal and ventral roots to the cord is such that a traction force applied to the combined nerve would be distributed above and below the axis of rotation so that its impact as a rotator would be somewhat neutralised.

THE PATHOLOGICAL ANATOMY OF THE NEURAXIS IN SCOLIOSIS

We had now satisfied ourselves that the radiological signs were, from the anatomical standpoint, compatible with a true representation of the pathological anatomy rather than artefactual.

We were fortunate in possessing a complete scoliotic spine, preserved in formalin, removed three years ago from a child suffering from a congenital

Fig. 4

Fig. 5

Fig. 6

The scoliotic spine of a child aged six weeks. Figure 4—The baby is alive and sitting in a hiatus hernia chair. Note the rotation in addition to the lateral curve. Figure 5—The spinal column after removal. Figure 6—Radiograph after the paravertebral soft tissues have been removed. There is no congenital vertebral anomaly and the pattern is apparently idiopathic.

Fig. 7

The posterior elements have been excised. Note that the dura is opposed to the concave side and the nerve roots on the convexity are clearly seen crossing the canal.

Fig. 8

The spinal cord has been exposed from the front. The anterior spinal artery retains its midline position and the cord has not rotated with the vertebral bodies.

disorder of the heart, who died at six weeks of age. Having previously obtained a similar specimen, which despite diligent histological examination, retained its secrets (James, Lloyd-Roberts and Pilcher 1959), we had resisted the temptation to examine this second specimen until we were in a position to ask a specific question to which the answer might be forthcoming. Such a question now presented itself.

Figure 4 illustrates the pattern of scoliosis when the child was living and seated in a hiatus hernia chair. Figure 5 is the specimen when removed, and Figure 6 the corresponding radiograph. The boy on this evidence suffered from infantile structural scoliosis which was probably idiopathic, but of unusual severity for his age. Subsequent histological studies of the spinal cord and paravertebral muscles did not reveal a primary neuromuscular disorder, nor did dissection show a vertebral malformation. We believe therefore that we are justified in regarding the scoliosis as idiopathic.

The surrounding paravertebral muscles were carefully removed and retained for further examination. The skeletal structures were thereby exposed. Having excised the posterior elements in the region of the apex

of the curve, the dural sheath was seen to be lying closely opposed to the lateral vertebral structures on the concave side, thus adopting the shortest route from the proximal to the distal vertebra of the primary curve. The intercostal nerves on the convex side must consequently traverse a greater distance in reaching their intervertebral foramina than those on the concave (Fig. 7).

Before proceeding to remove the central portions of the vertebral bodies on the ventral aspect it was necessary to ensure that the structural stability of the specimen was retained. This was achieved by wooden spatulae secured to the vertebral bodies by transfixing pins. The dura mater was then exposed from the ventral (anterior) aspect. The lateral parts of the vertebral bodies were preserved intact, exposure being obtained through the central zone. The dura mater was again found to be opposed to the concave side. The emerging nerves running towards the convex side were clearly seen, whereas those to the concave were hidden. The dura mater was then opened in the midline and the cord exposed. The anterior spinal artery was immediately evident in the midline. Its course remained central throughout thus confirming that, although the spinal

Fig. 9

An oblique view showing the contrast between the course of the nerves on convex and concave sides.

cord was curved laterally towards the convexity, it had not rotated in company with the vertebral column (Fig. 8).

Dissection therefore confirmed that in this specimen the spinal cord, although curved laterally, had not rotated, thus providing anatomical confirmation of the interpretation of the radiological signs.

We next concentrated our attention once again upon the course of the intercostal nerves and their dorsal and ventral roots at the centre of the primary curve. Their intraspinal course was necessarily longer on the convex than the concave side because the spinal cord, in adopting the shortest available route, lay on the concave side. The pathway was also more oblique in a caudal direction on the convex side (Fig. 9). The nerves on both convex and concave side remained in the same horizontal plane because the spinal cord and dura mater with its attachments to the nerve sheaths had not rotated but lateral displacement of the cord had increased the distance they had to cover on the convex side.

Once freed from the restraining influence of the dural sheaths within the intervertebral canal, the anterior primary rami had necessarily to turn sharply in a dorsal direction to enter the intercostal space which on the convex side was displaced backwards by the rotation of the vertebra. Furthermore, having traversed the intercostal space their course was further lengthened by the posterior displacement of the ribs and thus the intercostal grooves. The posterior primary rami innervating the paravertebral muscles may be even more affected, for they traverse the costotransverse ligaments before supplying the posterior muscles. Such an anatomical arrangement may well increase their susceptibility to traction or compression. On the concave side, however, the nerves ran a shorter and less tortuous course to enter the intercostal groove, the plane of which approximates much more closely to that of the spinal cord (Fig. 9).

The contrast between the course of the nerves on the convex and concave side invited speculation upon the possible effect of these changes upon the capacity of the nerves to transmit nervous impulses with equal efficiency. Was it possible that the nerves on the convex side were vulnerable to traction or compression because of their longer and more serpentine course?

THE ANATOMY OF ADVANCED SCOLIOSIS

There are two features of interest. Examination of a mature vertebra near the apex of a primary curve (Fig. 10) reveals that the body is rotated towards the convexity and the spinous processes towards the concavity. The curved indentation of the concave pedicle probably represents the site of the spinal cord. The ventral surface of the vertebral canal, however, does not follow this pattern and is indeed inclined in the opposite direction which suggests that its contents do not

Fig. 10

Transverse view of an apical vertebral body from a mature scoliotic spine. The vertebral body has rotated towards the convexity, the spinous process to the concavity. The ventral boundary of the spinal canal is tilted in the opposite direction and is indented on the concave side. (By kind permission of The Royal College of Surgeons of Edinburgh.)

Fig. 11

Convex side. The intervertebral foramina are oval and enlarged. Note the grooves to the right of the dorsal margins. (By kind permission of The Royal National Orthopaedic Hospital.)

follow the rotation of the vertebra as a whole. There is also a significant difference between the intervertebral foramina on the two sides. On the convexity the canal is elongated and oval (Fig. 11) whereas on the concave side it remains circular. This may possibly be due to pressure of the emerging nerve root upon the dorsal margin of the foramen on the convex side (where there is an identifiable groove) as the nerve follows the course

which is imposed upon it by posterior displacement of the ribs. Such an event would suggest that the nerve might at one time have been kinked or compressed at the point of contact.

THE NEUROANATOMY OF CONTRIVED SCOLIOSIS

There remains the possibility that the neuroanatomical changes are not secondary to skeletal deformity but present from the start. If, however, we could reproduce them within a normal spine upon which we have imposed the skeletal changes of scoliosis this would suggest that they are secondary, rather than primary. It is possible to contrive a replica of scoliosis of sufficient verisimilitude for our purpose by applying appropriate lateral and rotational stresses upon a normal spine removed from a very young child (Fig. 12). We can also apply these forces manually observing the effect of various deformities upon the neuraxis. Figure 13 illustrates the dura mater exposed posteriorly when the spine is straight. If we imposed lateral curvature (Fig. 14) the dura and its contents moved towards the concavity and the nerves on the convexity, whilst becoming more conspicuous as they crossed the vertebral canal, retained their normal caudal inclination without apparent tension. When rotation was added (Fig. 15) the course of the convex nerves became more oblique and tension developed within them. This was in marked contrast to their laxity and horizontal passage on the concave side.

It would seem possible, therefore, to reproduce anatomical changes comparable to those seen in our

Fig. 12

Radiograph of an infant spine upon which scoliosis has been imposed.

Fig. 13

Fig. 14

Fig. 15

Replica of scoliosis. Figure 13—Posterior prospect of the spinal canal before manipulation. Figure 14—With imposed lateral curvature. Figure 15—With the addition of rotation.

pathological specimen by manipulating a normal spine. This suggests that such changes are the result, rather than the primary cause, of scoliosis.

In correlating the hypothesis with some recognised features of scoliosis we will first discuss the role of rotation, and secondly the effects of disordered function of the intercostal nerves.

THE ROLE OF ROTATION

We have suggested that failure of the spinal cord to rotate in company with the vertebral column may be the cause of impairment of function of the intercostal nerve. We believe, however, that lateral deviation of the cord alone does not impose a comparable effect upon these nerves. Although, in the presence of lateral curvature, their course is longer on the convex side, it is only when a rotational component is added that this course becomes serpentine, possibly exposing them to the effects of traction and entrapment.

If this argument is valid, lateral curvature alone should be much less likely to undergo progressive structural deterioration than scoliosis with lateral and rotational components. This is a well-recognised fact which, however, has a special significance in the context of our hypothesis. We may mention three illustrative examples.

Compensatory curves. It is axiomatic that compensatory curves do not rotate. Their severity is dependent upon that of the primary rotated curve and their progression reflects deterioration within the primary curve. It is therefore significant to observe that although the cord is displaced laterally within the compensatory curve (Fig. 1), the rotational component is lacking so that the effect upon the nerve is less than that imposed by the primary curve.

Congenital lateral hemivertebra. The scoliosis is characteristically angular and short, lacking a rotational component. The angle of lateral curvature frequently remains constant throughout growth.

Infantile idiopathic scoliosis. Most such curves seen within the first year of life resolve spontaneously, but some deteriorate. It was however difficult in the early stages to identify those destined to progress (James, Lloyd-Roberts and Pilcher 1959; Lloyd-Roberts and Pilcher 1965). Prominence of the ribs on the convex side was not necessarily evidence of vertebral rotation, for it may have reflected no more than increased pulmonary expansion on the side opposite to that compressed when the baby habitually lay in the lateral position. Mehta (1972) has shown, however, that it is possible to distinguish between resolving and progressive curves when there is unequivocal radiological evidence of vertebral rotation. Rotation is present when the proximal ends of the ribs overlie the vertebral bodies. Furthermore, when the angles subtended by the ribs and vertebral bodies varies by more than 20 degrees between the convex and concave side 80 per cent will

progress. An analogy suggests itself between the rib collapse on the convexity in these patients and that in paralytic scoliosis with intercostal weakness.

THE INTERCOSTAL NERVES AND THE NEUROMUSCULAR COMPLEX

We will now consider the effects of unilateral intercostal nerve dysfunction upon the alignment of the spine, whilst not forgetting that intercostal nerves are composed of posterior (paravertebral) and anterior (intercostal) primary rami. The evidence is clinical and experimental, reinforced by certain observations upon changes demonstrable at the interface between nerve and muscle.

Clinical observations. The essential contribution of asymmetrical intercostal paralysis to both the cause and the progression of a paralytic scoliosis secondary to poliomyelitis is accepted (James 1956). In such patients the curve is always convex towards the side of intercostal weakness. Collapse of the ribs, which may lie almost vertically in severe examples, provides further evidence of the impaired function of the intercostal muscles. A similar alteration of rib alignment may also be seen in progressive infantile scoliosis at a very early stage (Mehta 1972). Thoracoplasty for pulmonary tuberculosis inevitably interfered with normal intercostal function. Thirty patients reviewed by Stauffer and Mankin (1966) all developed scoliosis convex to the side operated upon. Curves were of greater severity when the transverse process was excised.

Experimental evidence. There have been many attempts to produce an experimental model of scoliosis in animals, the results of which have, for the most part, been inconsistent and disappointing. Langenskiöld and Michelsson (1961) designed a methodical and comprehensive series of experiments in rabbits, one of which was consistently successful. If the proximal ends of the ribs and the costovertebral joints were excised unilaterally scoliosis with rotation convex to the side operated upon was consistently produced. The similarity between this and the scoliosis which follows thoracoplasty with excision of the transverse processes is obvious. Although section of intercostal nerves alone did not regularly produce scoliosis, it was evident that the successful experiment must have considerably modified the course of both the anterior and posterior primary rami of intercostal nerves distal to the intervertebral foramina.

More recently Babechko (1974), using electrodes to stimulate muscles on one side of the chest wall, has induced a scoliosis in pigs which is concave to the stimulated side. He has adapted this principle to the treatment of patients, using surface electrodes to apply intermittent stimulation on the convex side. Early results have shown that progression of the curve may not only be arrested, but even reversed, so that in some there is a demonstrable improvement. If confirmed these observations strongly support our concept of impaired

transmission in the intercostal nerves as a factor in the progression of scoliosis.

THE NEUROPHYSIOLOGY AND HISTOLOGY OF MUSCLES ACTING UPON THE SPINAL COLUMN

Reliable electromyographic tracings are difficult to obtain in this area, and even more difficult to interpret. There is, however, some evidence in support of denervation. Zuk (1962) reports significant differences in muscle potentials between the convex and concave sides in idiopathic scoliosis. Of 250 patients with idiopathic scoliosis there was evidence of denervation on the convex side in 88 per cent. In 11.5 per cent the sensory neurones were also affected. Redford, Butterworth and Clements (1969) confirmed some of Zuk's findings and tried to predict the prognosis of individual curves by a comparison of the electrical changes between the two sides. We are at present repeating this investigation.

Quantitative enzyme studies of paraspinal muscles have shown a pattern compatible with muscle breakdown on the convex side in six of eleven patients (Badger 1969). Saito (1966) claimed that there was degeneration of motor end-plates which was predominant on the convexity. Lastly, Fidler, Jowett and Troup (1974) observed an increase in slow muscle fibres on the convex side, suggestive of denervation.

Although previous work on neuromuscular changes is somewhat inconsistent and difficult to assess, the general trend of the results supports the concept of muscle degeneration of a neurogenic pattern, predominant on the convexity. We have not yet found convincing evidence to the contrary.

THE HISTOLOGY OF NERVES AND DORSAL ROOT GANGLIA

Intercostal nerves. Unequivocal evidence of nerve degeneration distal to the intervertebral foramina on the convex side would have strongly supported our hypothesis. Unfortunately, however, our results were inconclusive. The relatively short segments of intercostal nerves included in our specimen showed no such unequivocal histological evidence of either axonal or myelin degeneration. Vacuolisation of myelin and morphological changes in the axons were widespread and therefore regarded as artefactual or a reflection of immaturity. In addition, no neural abnormality was seen peripherally on examination of the paraspinal muscles. We also examined segments of anterior rami of intercostal nerves removed at operation. These specimens were inevitably short and although showing signs of damage this was probably due to surgical trauma because they were present in varying degrees on both convex and concave sides. Furthermore, we appreciate that the morphology of intercostal nerves varies in relation to the distance from the spinal cord, and we

cannot be certain whether our apparently comparable specimens were in fact taken at the same distance from the cord on both sides. Lastly, we are aware that entrapment syndromes are characterised histologically by evidence of both axonal degeneration and regeneration proceeding simultaneously, which again contributes to our uncertainty. Further work is clearly necessary.

Hitherto our studies have been confined to the anterior primary rami but we suspect that the posterior divisions may be equally, if not more, affected and warrant special consideration when material becomes available. In the meantime we will undertake axon counts on representative anterior rami removed at operation.

Table 1 Number of dorsal root ganglion cells counted at each level

Spinal level	Left	Right	Control
T1	1259	1608	66
T2	639	667	246
T3	701	692	346
T4	578	539	691
T5	512	447	287
T6	501	450	555
T7	733	904	566
T8	461	545	416
T9	700	779	380
T10	611	528	609
T11	575	458	519
T12	760	742	434
L1	768	1129	616
L2	954	1224	370
L3	1779	1181	783
L4	1778	1564	370
L5	919	793	1187

Dorsal root ganglia. The criticisms which we have mentioned in relation to the peripheral nerves do not apply with the same force to the dorsal root ganglia. Ganglion cell degeneration, as indicated by central chromatolysis and eccentrically placed nuclei, is considered a sensitive index of degenerating dorsal root axons (Figs. 16 and 17). We therefore counted the number of chromatolytic cells in representative sections from all the thoracic and lumbar dorsal root ganglia on the convex and concave side of our specimen, and also from a normal age-matched control. The results are expressed as the percentage of abnormal cells in relation to the number of cells counted in each individual ganglion (Table 1) and presented in graphic form (Fig. 18). It is

Fig. 16

Fig. 17

Figure 16—Section of dorsal root ganglion from the concave side of the apex where normal ganglion cells are demonstrated. Figure 17—Section of dorsal root ganglion from the convex side of the apex where several ganglion cells show central chromatolysis and eccentric nuclei. (Cresyl fast violet, $\times 600$.)

Fig. 18

Fig. 19

Figure 18—The percentage of ganglion cells showing chromatolysis from T1 to L5, from the convex side of the specimen, from the concave side and from an age-matched control. Figure 19—Randomised recount using new sections.

evident that apparently abnormal cells are to be found at all levels in the specimen and in the control. The numbers, however, are similar at levels above and below the point of maximum curvature of the scoliotic spine, and throughout the control specimen. Other mechanisms, including immaturity, must therefore be considered as possible contributory factors in producing these histological changes. On the convex side of the curve, however, the number of abnormal cells rises sharply to a level of 14 per cent at the apex compared with an average of approximately 3 per cent elsewhere in the specimen and in the control. Conscious of the danger that a knowledge of the level and side of the section under examination might influence the objectivity of the observer, counts were repeated using a different stain and new sections. Sections were examined at random,

their site being unknown and the outcome was almost identical (Fig. 19).

There would seem therefore to be some evidence of axonal damage within the dorsal root on the convex side at the level of the apex of the primary curve. If this is accepted and the responsible lesion assumed to be situated distal to the confluence of dorsal and ventral roots, we may perhaps suggest that the ventral root axons are similarly affected despite our inability at this stage to demonstrate this. Even if this should not be so, we should recall that MacEwan (1968), having induced scoliosis experimentally by division of dorsal roots alone, speculated that interference with proprioceptive sensation might have a significant role in the aetiology. It is indeed possible that the course of the dorsal roots may render them more susceptible to damage in scoliosis.

CRITICISM OF THE PROPOSITION

Although the direct and circumstantial evidence seems to us persuasive, we must concede certain misgivings. We have based our argument upon the anatomical findings in but one specimen of scoliosis which, although classified as idiopathic through lack of contrary evidence, is nevertheless of unusual severity for a child so young. Furthermore, other congenital anomalies were present. Angiographic studies do, however, suggest that the spinal cord does not rotate in older children, and our anatomical observations seem to provide some support and a logical explanation. Histological examination of intercostal nerves is beset with technical difficulty and at

this preliminary stage we can draw no conclusions from them. We are nevertheless encouraged by finding an increase in degenerating cells in the dorsal root ganglia on the convex side of the primary curve in our specimen.

Although there is much to engage us in the study of material which is readily available, the validity of our proposition can only be assessed if and when further specimens of entire scoliotic spines become available and are submitted to detailed examination of the spinal cord and nerve roots. If our findings are confirmed we may in time develop a method of arresting scoliosis in a manner less arduous, to both patient and surgeon, than those available to us today.

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