

INTRAVITAL MEASUREMENTS
DURING INSTRUMENTAL
CORRECTION OF
IDIOPATHIC SCOLIOSIS

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Foreword

In 1958, on joining the staff of the New York Orthopedic Hospital, it was my good fortune to become associated with several men who were deeply interested in the problems of scoliosis and spine fusion, in fact, an interest that has been maintained since the original work of Hibbs with this disease.

This investigation has consisted of two parts, the first of which, the clinical, began when Professor Frank E. Stinchfield made me responsible for the Scoliosis Service at Columbia University. With a background of over 2,500 surgically treated patients with spinal deformity, the majority of whom have been carefully followed, it was believed that the New York Orthopaedic Hospital could provide valid conclusions about the efficacy of existing treatment.

In 1965, the second phase, the experimental, was begun in the Biomechanics Laboratory of the University of Gothenburg. Professor Carl Hirsch has provided the facilities, encouragement, and personal guidance which enabled this work to be carried out.

Any study of this nature depends upon the cooperation and assistance of many people. I would like to thank the staff at the Orthopedic Clinic for their suggestions and cooperation.

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I Introduction

Hippocrates is usually credited with the introduction of the term "scoliosis." However, the treatments he and his contemporaries used for this disability, such as succussion, confirm that anteroposterior and lateral curvatures were not always separated. During the 16th century, Paré described the deformity that we recognize today as scoliosis, and further, recommended treatment by a metal brace. During the 18th century, Andry, in his textbook of Orthopaedics, added further definition to the deformity and postulated on its pathogenesis. However appropriate, or inappropriate, it is doubtful that Andry had scoliosis in mind with the famous illustration of a young curved tree trunk in the act of being straightened.

During the 19th century, it became apparent to orthopaedists that any rational treatment must depend upon a concept of the etiology. It would perhaps be fair to say that almost every contributor through the immense literature on scoliosis has since evolved his own theory of pathogenesis and applied it to justify an "improved" form of therapy. The 19th century theories included Stromeyer's (1838) inequality of the ribs, Guérin's (1843) contractural theory, Meyer's (1866) mechanistic approach and, of course, Lorenz's (1886) attempt to amalgamate the opinions of others with his own. The turn of the century saw emphasis placed on the final pathological forms of the disease, as seen at autopsy, and so well described by Albert (1899), Virchow (1911, 1914) and others. Coincidentally with these pathological descriptions in man, several articles were written describing the presence of scoliotic deformity in swine and house birds.

The modern era, in the treatment of scoliosis, would appear to have been ushered in by Hibbs' (1924) publication of the initial experiences in the treatment of severe structural scoliosis by spine fusion. To the present day, while techniques of correction may vary, there remains only one generally accepted method of maintaining correction, which is of course, spine fusion.

THEORIES OF PATHOGENESIS

In Cobb's (1948) etiological classification of scoliosis, approximately 90 % of cases fall within the idiopathic category. One might assume, therefore, that the pathogenesis of the remaining 10 % was clearly established, however, such is not the case. Until recently, the second largest category within the classification has been the paralytic or neurogenic group.

Muscle paralysis

In 1941, Colonna and Vom Saal attempted to correlate muscle paralysis with type of curvature. It is well recognized that there were many curvatures that they were unable to correlate with any specific paralysis. James (1956), in a careful review of his cases, refuted some of the conclusions of Colonna and Vom Saal. Arm and leg muscle paralysis were not related to the production of scoliosis, nor were the mid-line muscles such as the erector spinae and the anterior abdominals. In a significant number of cases, however, it was apparent that the intercostals, the lateral abdominals and the latissimus dorsi were weak on the convexity. In regard to specific curve patterns, James found that intercostal muscle weakness, although this is a difficult assessment, was associated with thoracic curves in a significant number of cases. Thoracolumbar curves were found with convex lateral abdominal weakness, and it was his feeling that gravitational forces were important in the development of this curve. In lumbar curvature, apparently the important muscles were the lateral abdominal flexors (quadratus lumborum, the lateral portion of the anterior abdominal muscles and possibly the latissimus dorsi). Michele (1962) has stressed the importance of the iliopsoas. With regard to mid-line muscle paralysis, James agreed with Steindler (1929) that anteroposterior, rather than lateral curves, developed from this weakness. Garrett, Perry and Nickel (1961) also found in their series of cases a correlation between thoracic curves and intercostal muscle weakness, the convexity being towards the weaker side.

When scoliosis develops following poliomyelitis, it may be easier to understand the development of spinal curvature, but the fact that a perfectly clear-cut relationship does not exist seems important. This might be explained by the difficulties of muscle grading, the generalization of paralysis, or, perhaps, it merely reflects the underlying problems of scoliosis in general. Risser (1964) and Gruca (1958, 62, 63) have advanced a muscle weakness theory for the pathogenesis of idiopathic scoliosis. It is Gruca's belief, in agreement with Andry (1743), Movshovich (1960) and others, that idiopathic scoliosis is caused by impaired equilibrium of muscular

activity at the level of the initial curvature. On the basis of his investigations, he has concluded that the musculature on the convex side of the curve is weakened and degenerated, and there is increased tension on the concave side. He has illustrated this theory with a model of the spine utilizing rubber bands as muscular motors. Zuk (1962), in studying the electrical activity of the back musculature, found greater activity on the convex side. It is his impression, however, that increased electrical activity may be a sign that a muscle is reaching the limit of its power and, thereby, represents weakness rather than strength. On this basis, he also postulates that scoliosis is due to muscle imbalance, the weaker muscles being on the convex side of the curve, and that the increased electrical activity on the convex side represents the body's attempt to compensate for the curvature. In subsequent studies, Zuk (1965) noted signs of fatigue on the convex side of progressing curves, whereas in fixed curves he found increased tone.

Liszka (1961) performed an interesting series of experiments on young rabbits with segmental elimination of spinal cord function. By unilateral transection of multiple spinal roots, scoliosis was produced which was convex to the operated side. He also noted, as a result thereof, some affect on the growth of the convex vertebral bodies. It was his impression that idiopathic scoliosis was caused by a primary injury to the cord. It is of interest that Riddle and Roaf (1955), in contrast with these findings, found dorsal concave muscular weakness associated with spinal curvature. Gorynski and Bojkowa (1957), in examining specimens obtained at surgery, have found histological evidence of degenerative changes in the muscle on the convex side of idiopathic curves. Bisgard (1935), Schwartzmann and Miles (1945) produced varying degrees of scoliosis experimentally by muscle excision, but in many cases, the curves corrected spontaneously or were trivial.

From these conflicting reports in the literature, it may be concluded that damage to the neuromuscular unit may be responsible for some types of scoliosis, but whether such is the case for the idiopathic group as a whole, does not appear to be established. In all probability, some cases in the idiopathic grouping may be attributable to hidden central nervous system disease or damage, but that such could be the general case seems unlikely.

The costotransverse ligaments

Wenger (1951) observed that the post-thoracoplasty development of scoliosis depended upon the intactness of the transverse processes and the various ligaments attached thereto. In the treatment of existing scoliosis by transversectomy, he noted an immediate degree of correction that persisted. Lagenskiöld and Michelsson (1959, 61, 62, 63), in attempting to produce

spinal deformities in animals comparable to scoliosis in man, found that resection of the deep back musculature, transection of the intertransverse ligaments, and, transection of the ribs lateral to the tubercles caused no scoliosis, whereas, resection of the dorsal ends of the ribs, transection of the ligaments of the heads of the ribs, transection of both external and internal intercostal muscles, radical hemilaminectomy, transection of the transverse ligament, and, in the lumbar area, transection of all the muscles and ligaments attached to the arches and transverse processes consistently cause scoliosis. It was their impression that resection of the dorsal ends of the ribs caused the most severe functional and structural scoliosis. As a result of their operative procedures, they noted the development of rotation with wedging, vertebral deformity and "rigid" curves. The apical vertebrae were higher on the convex side with decreased size of the concave arch. They also noted displacement of intervertebral discs towards the convexity with uneven and irregular endochondral ossification on the concavity. In reviewing this data, they concluded that the significant factor amongst the thoracic operative procedures was section of the posterior costotransverse ligaments. An interesting finding in this regard was the disappearance of the scoliosis under deep anesthesia or with death of the animal. This they attributed to the role of the muscles in the development of the deformity, particularly the intercostals. In applying their findings to idiopathic scoliosis in man, section of the concave costotransverse ligaments was undertaken to produce a counter-scoliosis. It was their preliminary impression that this procedure resulted in correction of the existing deformity. Flinchum (1963) also reported good results from concave rib resections, however, in cases to be reported, the author has not been able to duplicate these results. Lindahl and Raeder (1962), following a mechanical analysis of the forces involved in idiopathic scoliosis, determined that the transverse processes acted as tie points which might be lengthened on the convex side and shortened on the concave to produce deformity. It was assumed that the intertransverse ligaments and muscles might be important in the production or maintenance of deformity. Acting upon this hypothesis, they, as did Wenger, resected concave transverse processes, however, in a subsequent report (1963), Lindahl stated that this surgical procedure had apparently not influenced the natural course of the disease.

The vertebrae

Knutsson (1961) has shown that growth from the superior and inferior surfaces of the vertebral body are equal. Bick (1961) remarked that the superior and inferior "epiphyses" are wrongly termed because of the

absence of an ossification nucleus. He prefers the expression "vertebral growth plate", and as the vertebral rings add nothing to the growth of the vertebral body, they should more correctly be called "traction apophyses." He quotes the Hueter-von-Volkmann law, the affect of pressure and traction on growth plates producing asymmetric expansion, as an appealing concept for scoliosis. Bisgard and Musselman (1940) believe that unilateral growth disturbances are either totally responsible, or at least contributory, to the development and progression of idiopathic scoliosis. They have said that wedge-shaped vertebrae could not develop as a result of compression, and for substantiation cite Wolff's law, thereby reraising an old controversy. They believed it more probable that abnormal pressure causes wedging by retarding growth. Arkin (1949), discussing the mechanism for structural changes in scoliosis, quoted the Research Committee of the American Orthopedic Association (1941), the majority of the members at that time, believing that scoliosis was the result of a disturbance in the growth plate. He calculated the pressure on the concave side of the disc as being approximately six to seven times the superincumbent body weight. Arkin and Simon (1950) reported their experimental work producing scoliosis by the implantation of radon seeds, and Arkin, Pack, Ransohoff and Simon (1950) and others have reported clinical cases of radiation induced scoliosis. Katzman and Waugh (1966), in reporting a large long-term follow-up study of children treated for tumors by radiation therapy, found 28 survivors, 23 of whom showed alteration of the vertebral bodies. In the latter part of the first year following radiotherapy, subcortical lucent zones appeared parallel to the epiphysial plates, which progressed to growth arrest lines. This gave the configuration of a "bone-within-a-bone" as the growth arrest lines were incorporated within the growing vertebral bodies. It was our impression that this phenomenon represented an arrest of endochondral ossification of the vertebral bodies, and that the size of the "bone-within-a-bone" corresponded closely to the size of the vertebral body at the time of the original therapy. As growth continued, but in a distorted manner, the bodies became diminished in vertical height and developed irregularities or scalloping of their superior and inferior surfaces. Often the final changes were similar to those seen in Cretinism, Morquio's, or Hurler's disease. Twenty patients were noted to have scoliosis. The curves that developed were all concave toward the side of the tumor, provided there was no known neoplastic invasion of bone. Three of these curves measured 40 degrees or more by the Ferguson (1939) method. It was believed that dosage levels were related to the severity of the changes observed. Tumor dosages greater than 2000 R usually produced skeletal changes in these

growing children. No critical dosage level has been observed in humans, below which radiation changes in bone are not seen, and yet, the basic malignant disease was cured. The time necessary for development of the radiation changes implied cure of the original disease.

With the appreciation that injury to a vertebral growth plate can interfere with normal growth, and when predominantly unilateral, produce scoliosis, Arkin and Katz (1956) concluded that pressure inhibited growth, but not by an all-or-none law. They believe there was no sign of a threshold below which pressure was ineffective. A growing epiphysis, subject to stress, yields to that stress. Pressure parallel to the direction of growth inhibited such growth and pressure perpendicular to the direction of growth deflected growth causing lateral or spiral displacement. As an assessment of the magnitude of forces involved, they cited the breaking tests of staples used for a Blount (1949) epiphysial arrest. They assumed that even gravitational pressure had an inhibitory affect on the growth of bone. Stilwell (1962), in a series of muscle resection experiments, produced vertebral angulation and rotation by creating unopposed forces. In 1939, Haas produced scoliosis in dogs by a unilateral injury to the epiphysis, and he suggested the possibility of using this as a corrective procedure. Nachlas and Borden (1951) caused scoliosis in dogs by clamping vertebrae and then corrected this scoliosis by a similar procedure on the convex side of the curve.

With regard to the therapeutic applications of the principle of compensatory growth arrest, the results have been only variably successful. Smith, Von Lackum and Wylie (1954) were unsuccessful in attempts to staple the vertebral growth plates. Le Messurier (1951) found that unilateral epiphysial destruction produced no alteration in the progression of the curve, and Moore (1951) stapled the transverse processes without success. More recently, Mc Carroll and Costen (1960) attempted surgical epiphysial arrest with inlayed bone grafts on the convex side. In this connection, however, it must be recalled, that the situation at the intervertebral joint is considerably different from the epiphysial plate of a long bone, and this may explain some of the failures. Roaf (1963), however, has, on the basis of 189 cases, recommended his technique of growth arrest.

Somerville (1952) believed that the deformity of scoliosis is attributable to a relative failure of growth of the posterior elements, which in turn, produced lordosis, rotation and lateral flexion. By cauterizing the vertebral arches of rabbits, he produced some degree of scoliosis. Wittebol (1956) performed similar experiments in dogs and pigs and believed he had refuted the theory of lateral deviation being a result of unilateral predominance in growth of one or several epiphysial plates. Ottander (1963),

on the suggestion of Knutsson (1963, 66), in a series of experiments produced some scoliosis, which he attributed to asymmetrical growth of the neuro-central junction.

Bick, Barash and Lehman (1958) drew reattention to the role of the disc, by describing two cases of congenital scoliosis, one of which demonstrated concave annular compression and the other, definite displacement of the disc to the convex side. Perey and Rydman (1962) and Perey (1963) performed discography at the apex of three curves and found asymmetric positioning of the nucleus. In two patient this was convex, and in one, concave.

Farkas (1954), in an extensive pathological and radiographic study of scoliotic spines, noted vertebral body channels which he assumed to be the predisposing cause, and considered weight bearing the exciting or mechanical cause of idiopathic scoliosis. He believed the basic pathological process involved separation of the epiphysial rings and vertebral cortex from the interior of the vertebral body which was probably attributable to atrophy.

Under unusual circumstances, such as seen in radiation induced scoliosis, it is obvious that unilateral epiphysial injury may produce a deformity that, in many respects, resembles idiopathic scoliosis, it seems unlikely that the pathological changes in the individual vertebrae are the primary cause of the deformity. More likely, these changes are the result of abnormal pressure considerations from outside the vertebral column. Support for this impression is furnished by the work of Arkin (1964) who was able to overcorrect the deformity of idiopathic scoliosis by prolonged recumbency, only to have it redevelop on assuming the erect position.

Forces

Steindler (1929), Michele (1962), and others have approached scoliosis by a mechanical analysis. A column has been described as a compression member which tends to fail because of unstable equilibrium. In general, the distinguishing characteristic of a column is its slenderness which is the ratio of the length to the radius of gyration, the latter being with respect to the centroidal axis, about which the column tends to bend. As the load on a column increases, the column shortens in accordance with Hooke's or some other physical law and remains in stable equilibrium. If, however, some initial crookedness or eccentricity is present, bending begins immediately. For initially straight columns, as the load is increased, the column remains straight until a certain value, called the critical load, is exceeded, whereupon the column is in a condition of unstable equili-

brium. Under these circumstances, minor extraneous factors will cause the column to buckle. This problem is greatly aggravated by the fact that no warning of this condition is present, and hence, failures are nearly always unexpected. According to Euler's formula, the critical load depends upon the fourth power of the radius. The end conditions modify the formula. In general, the vertebral column is looked upon as having one end fixed and one end free. The deflection curve of this end condition encompasses the upper 0.707 of the length, whereas with both ends fixed, the deflection curve involves only the middle half. With an axially loaded column, there is no bending, and the stresses are uniformly distributed over the area of the cross section. However, with eccentric loading, a tendency is produced for column bending. With a long column, the stress on one side may become tensile instead of compressive. According to the principle of the middle third, the critical eccentricity is only one-sixth of the diameter. (Shigley 1963, Parker 1961.)

Steindler and Michele have noted there are several situations present in the human spine that prevent anything but a casual analogy to an ideal column. The spine is in fact a pyramid, the end conditions are difficult to establish, natural curvatures exist, the muscles and ligaments function as ties, and, the spine is not simple but segmented. Lucas and Bresler (1961) have calculated the critical load of a segmented column composed of alternating rigid and elastic elements. At the statistically most common apical level of thoracic scoliosis, the superincumbent body weight, according to Crawford (1965) is about 25 % and interpolating Ruff's (1950) lumbar figures, about 40 % of the total body weight. Morris, Lucas, Bresler (1961), and others, by manometric measurement, have ascertained the thorax and abdomen to absorb about 50 % of this superincumbent weight. From these considerations, it might be postulated that the force on the apical vertebra of an adolescent scoliotic might be of the order of 7 to 10 kg. With well established curvature, Arkin (1949) has calculated compressional forces on the concave side of the epiphysis of up to 14 times this magnitude. Using Nachemson's formula for lumbar disks, the apical load would be 57 kg with upright standing. (1966)

The rotational element of scoliosis prompted Lovett in 1902 to state, "In the attempt to solve this problem, a very large amount of literature has accumulated without obvious practical result." He refuted Meyer's (1866) theory of two columns with different elasticity, based upon examination of specimens. He concluded that side-bending and torsion were compound movements and could not be disassociated, and that the column of vertebral bodies was the determining factor and not the articular processes. This theory has, in general, prevailed until the present time. Many authors,

besides Lovett, have resorted to models to explain rotation. (Risser 1957, Lindahl and Raeder 1962, Arkin 1950, Tideström 1958, and others.) Steindler (1929) considered that rotation of the vertebral bodies to the concave side is not the expression of a natural tendency but rather the result of muscular effort. Michele has shown in lumbar curves that rotation may be due to the unbalance pull of the iliopsoas. Arkin (1950) believed there were two factors in scoliotic rotation, one, the tendency of muscles and ligaments to describe a straight line, and the other, the wedge shape of the vertebral bodies. Roaf (1958) believes that scoliosis may be explained on the basis of a primary rotation deformity and has stressed the component of lordosis. In the presence of an established deformity, the long fibers of the erector spinae muscle tend to increase the deformity. In a straight spine, this muscular pull is opposed by gravity, but in the presence of scoliosis, gravity serves to reinforce the deforming action of the long spinal musculature. Roaf (1958) has also emphasized the role of rib pressure. Because of the axis of rotation of the thoracic spine relative to the attachment of the ribs, intercostal muscle action will tend to increase the deformity of established curves. Lindahl and Raeder (1962) noted that the deformation in scoliosis could not be produced by acute or physiological movements of the spine. They also pointed out that in the upper part of a curve the rotational relationship of the inferior to the superior vertebra is clockwise, while in the lower half of the curve, the relationship is anti-clockwise. They believed that rotation in scoliosis was dependent upon the assumption of a larger radius of curvature by the intertransverse ligaments, the transverse processes functioning as cross-trees or spacers. Gravity has been generally accepted, since earliest times, to be an important pathogenic factor in the production of scoliosis. The most conservative of treatment for the disease has been bedrest, which Cobb (1949) stated he had found to be very effective in preventing progression. The importance of gravity in the development of scoliosis in man has been reinforced by the absence of the deformity in quadrupeds, except in unusual or experimental circumstances.

Because of the mechanical design of the human vertebral column, a precarious equilibrium must exist, that depends upon extraneous factors for its stability. Relatively small unbalanced forces could be sufficient to produce significant deformation. (Fiess 1907).

Although Roaf (1958) has discussed the action of the ribs in producing a force couple to increase an existing deformity, few have concerned themselves with this facet of the problem. The ribs have two axes of motion, the one, elevation about the vertebral fulcrum, and the other, rotation about the sternovertebral axis. It is of interest that elevation of the anterior

ends of the seventh to tenth ribs is associated with posterior motion of the sternum, while elevation of the sixth thoracic and above is associated with forward motion of the sternum, the movement occurring at the manubrio-sternal joint. With quiet respiration (below 50 liters per minute), the diaphragm, inferior intercostals and occasionally the scalene muscles are active. However, quiet expiration depends on the elasticity or compliance of the lung, which is known to be abnormal in scoliosis. (Gardner, Gray and O'Rahilly 1960) In studying vertebral rotation, Rolander (1966) observed that the average height of the disc increased when horizontal torque was applied, and the increase was approximately proportional to the degree of rotation. This he attributed to the helicoidal arrangement of the fibers in the annulus described by Horton (1958) and Galante and Hirsch (1966). It is possible that the reverse may also be true, and lateral deviation might generate a horizontal torque, which would, in turn, explain at least some of the rotation about the vertical axis.

HEREDITY

Several case reports exist in the orthopedic literature of scoliosis in identical twins. Generally speaking, these curves have been similar but not always identical. Codorniu (1958) described uniovular twins, both of whom had thoracic curves, the one measuring 35 degrees and the other 42. Esteve (1958) reported uniovular twins with thoracic curvatures, one of which measured 46 degrees and the other 58. In the latter case, the roentgenograms show a fairly large lumbar curve which raises the question of a double primary. Murdoch (1959) reported additional twins with idiopathic right thoracic curves measuring 55 and 46 degrees. He stated that all previously reported cases had been in girls. However, Wiest (1954) had presented a clinical and electromyographic study of the paravertebral musculature in uniovular twin boys, one of whom had idiopathic scoliosis. The curve in this 12-year old was left thoracic with its apex at the seventh or eighth dorsal vertebra. The electromyographic studies, showed hypertonic activity at the level of the apex on the right side of the twin with scoliosis. Hull (1961) subsequently reported scoliosis in 15-year old binovular twin girls. In this family, there were five other siblings with one other pair of binovular twins, none of whom had scoliosis. Molski (1957) found 16 families in Poland of which 38 members had scoliosis. Wright and Niebauer (1956), in a study of the association of congenital heart disease with scoliosis, found that out of 422 cases of congenital heart disease, 5.5 % had a scoliotic deformity which exceeded 10 degrees. In those patients over 14 years of age, the incidence of scoliosis was 19 % as compared with a controlled incidence of 6 %. In no case was the scoliosis related to cardiac

surgery or cyanosis. It was their impression that this increased incidence was statistically significant.

Gilly, Stagnara, Frederich, Dalloz, Robert and Goldblatt (1963), in studying the medical aspects of structural scoliosis in children, found that 21 % of their cases had a family history of the disease. They and James and Wynne-Davies (1965) have concluded that the inheritance of idiopathic scoliosis shows aspects of dominant inheritance rather than being multifactorial.

These reports suggest a definite hereditary basis, but it is interesting that Anders (1965) was unable to demonstrate any chromosomal abnormality in 11 patients with idiopathic scoliosis. With future technical refinements, however, it may be possible to do so.

METABOLISM

Kiepuska (1957) performed various biochemical studies on 50 children with idiopathic or dystonic scoliosis. The children varied in age from 4 to 14 years. He found that the calcium, phosphorus, alkaline phosphatase, blood sugar, ketonic compounds and alkali reserve differences obtained were insignificant when subjected to statistical analysis. Similarly, Fiala and Jadrny (1962) confirmed normal values for calcium, phosphorus and alkaline phosphatase. They also found that the cholesterol, creatine and ketosteroids were within normal limits.

Stearns, Chen, McKinley and Ponseti (1955) also found calcium and phosphorus values to be normal. However, investigating the metabolism of protein, they noted a definite negative balance. They found that scoliotic children required high protein diets in order to retain sufficient nitrogen for normal growth and that in all probability, the normal diets of these children did not contain this amount of protein. The negative balance was manifest by increased excretion of urea nitrogen. In addition, they noted increased excretion of taurine and cysteic acid and/or methionine sulphoxide. This represented a significantly high loss of sulphur containing amino acid derivatives. Electrophoretic studies of serum amino acids in five of the author's scoliotic patients failed to indicate any significant abnormality (1962). This is in keeping with the findings of Ponseti (1966). Glauber, Fernbach, Massanyi and Medgyesi (1962), in an electrophoretic study of scoliotics, found increased alpha 1 globulin and total protein bound hexose, and alpha 1 glycoprotein of the serum, and they assumed that these changes were a consequence of a disturbance in the metabolism of mucoprotein. Benson (1965), in studying urinary hydroxyproline excretion, found significantly raised levels in idiopathic scoliosis, particularly boys, but normal levels in neurological and osteopathic scoliosis. Franchi, Agnisti, Donnini and Simo-

netti (1963) studied the serum anti-elastase activity in idiopathic scoliosis. They found an increase in the percentage of the anti-elastase inhibitor in blood serum. They considered that idiopathic scoliosis was due to a degeneration of the elastic structure.

Ponseti (1962) has drawn attention to the changes in the anterior chamber of the eye, such as dysplasia of the peripheral iris, presence of abnormal blood vessels, and the attachment of the pectinate ligament. These changes are present in Marfan's disease, idiopathic scoliosis and slipped femoral epiphyses. In pointing out that similar changes can be produced in animals with aminonitriles, he has stated that idiopathic scoliosis is due to an inborn error of mucopolysaccharide metabolism. Frederich, Creysse, Gilly, and Goldblatt (1963) also studied urinary amino acid excretion in scoliotics and have observed diverse anomalies in protein metabolism. They, too, have concluded that a metabolic error is primarily responsible for idiopathic scoliosis.

On the basis of these reports, fairly substantial evidence of negative nitrogen balance has been presented. Although serum amino acid concentrations appear normal, the increased excretion of sulphur containing amino acid derivatives suggests an abnormality of mucopolysaccharide metabolism. Ponseti (1966) now feels that the costotransverse ligaments may be specifically affected, but it is still early to assess the significance of these findings.

PATHOLOGY

Our pathological knowledge of idiopathic scoliosis has been derived from two main sources as pointed out by Stilwell (1962). These are the classical autopsy descriptions of the stabilized deformity by Nicoladoni (1904), Virchow (1911, 14) Putschar (1944), and others in the literature of German pathology, and, serial radiological examinations by orthopedists and radiologists. Unfortunately, the former source, although interesting, sheds little light on the more dynamic aspects of the development of the scoliotic deformity. Recent studies have tended to concern themselves more with the presence or absence of changes during the active phase of curve development and progression.

In 1959 and 1961, James reported autopsy material examined by Sissons from an 11-month old child with infantile idiopathic scoliosis. Microscopic evaluation of the vertebral epiphyses was normal. McCarroll and Costen (1960), reporting on surgical epiphyseal arrest procedures in four children secured biopsy material from the convex side of rapidly progressing idiopathic curves. They reported disorganization of the cartilage columns of the end plate. An autopsy (1962) performed on a 15-year old girl with

right thoracic scoliosis provided the author the opportunity to examine the vertebral bodies of the entire primary curve. Comparable sections were taken of the convex and concave sides of the curvature, and these were compared with respect to the size and organization of endochondral bone formation. In all cases involving the apical vertebrae, thinning was evident on the concave side with horizontal flattening of the cartilage cells. On the convex side, these changes were much less evident, the cartilage columns approaching that seen in a normal child of the same age. In those sections removed from the extremities of the curve, while some disorganization was believed to be present, these changes were inconclusive. On the basis of the microscopic and radiological examination of the specimen, it was not possible to contrast the bone density on the concave and convex sides of the curve nor establish epiphyseal vascular lesions as reported experimentally by Brodetti and Cauchoix (1960, 62) and Amato and Bombelli (1959). Bick, Barash and Lehman (1958), on autopsy examinations performed on a male fetus and a 4-1/2-month old infant, have reported concave annulus compression in the former and displacement of the intervertebral discs to the convex side in the latter. In a series of operative procedures performed by Roaf (1963) to produce unilateral growth arrest on the convex side of actively progressing scoliosis, he found lateral displacement of the nucleus pulposus. These findings are in keeping with those of Perey and Rydman (1962). Stilwell (1962) has interpreted the displaced epiphyseal rings, reported by Farkas (1954), as probably being calcified disk protrusions.

Gornyski and Bojkowa (1957) performed histological studies on 24 patients with idiopathic scoliosis. The specimens were excised from the apex of the primary curve. In examining the muscle, variegated, narrowed, undulant and fragmented muscle fibers were found in association with loose and dense connective tissue. They interpreted these findings as representing degenerated atrophic muscle. Unfortunately, no correlations were made with the origin of the specimens, nor the degree of curvature. The significance of these findings have been discounted by Stilwell (1962).

Several authors have pointed out the interesting association between spondylolysis and spondylolisthesis and scoliosis. Bosworth, Fielding, Demarest and Bonaquist (1955) found 25 of 115 patients had scoliosis in the lumbar region. They were unable to establish a correlation between the amount of slipping and the severity of the scoliosis. Bozdech (1962) found a similar association, while Risser and Norquist (1961) stated that antalgic scoliosis can result in concave contractures, vertebral wedging and increasing scoliosis until the completion of vertebral growth. In 9 of their 10 cases, spondylolisthesis was responsible for the precipitating back pain.

II The problem of treatment

By way of introduction to the methods and problems of treatment of scoliosis, it seems desirable to assess the dimensions of the problem. Shands and Eisberg (1955), in reviewing 50,000 chest films, found a scoliosis incidence of 1.9 % in the state of Delaware. This was an unselected series of individuals over 14 years of age. Of these films, only 0.5 % of the curves exceeded 20 degrees. Patynski, Szczekot and Szwaluk (1957), in studying 5,000 school children ranging in age from 7 to 15 years, found an incidence of scoliosis of 2.56 %. Of these, 0.08 % had curvatures that measured from 30 degrees to 60 degrees, and 0.04 % had curves in excess of 60 degrees. Bruszewski and Kamza (1957) surveyed 15,000 serial radiographs and found an incidence of 3.7 % of which they considered 3.08 % as mild and 0.46 % as moderate and 0.15 % as severe scoliosis.

In reviewing a selected scoliosis population, many of whom were referred to the New York Orthopedic Hospital for surgical treatment, Smith (1958) found that less than 20 % had surgical treatment recommended, and this was actually carried out in 15 % of the cases. Under our present guidelines for surgical treatment, a more generally accepted figure is between 5 % and 10 %.

The present treatment of scoliosis consists of two parts, the first, correction of the curve, and the second, maintenance of the correction achieved. Cobb (1958) has stated that the results of treatment are proportional to the enthusiasm of the one treating. It is proposed to examine both facets of the problem separately.

Prior to the 1920's, attention was directed towards various methods of achieving correction. These, in general, depended upon numerous corsets, braces and casts. Surgically, Guérin (1843) and Malgaigne (1844) had already found that posterior vertebral muscle myotomy was completely ineffective. Bigg (1865), in an excellent review of previous forms of therapy, showed illustrations of various couches that are early forerunners of the present day localizer and surcingle tables. In 1877, Sayre, in his

book on spinal curvature, recommended the use of plaster bandages for support of the spine.

Since 1920, Hibbs (1924), Von Lackum (1948) and Risser (1953, 55) have been largely responsible for the development of the turn-buckle, anti-gravity, localizer and surcingle correctional jackets. Various modifications of these have been developed by others.

There seems to be little doubt that the turn-buckle jacket is the most effective external method of correcting a primary curve. However, as has been stressed by Risser (1948, 57), Cobb (1948, 60), Smith (1958), Schmidt (1959), and others, the method has a tendency to increase the secondary curves. Naturally, it is important that the amount of correction should not be greater than the secondary curves permit. This problem, along with the cumbersome nature of the turn-buckle jacket, has led to the development of the anti-gravity and localizer casts by Risser (1953, 55) and the transection and surcingle jackets of Von Lackum (1948).

In 1958, Blount, Schmidt, Keever and Leonard reported on the use of a brace in Milwaukee that combined the two principles of traction and local rib pressure. Effective use of this brace, however, requires an experienced bracemaker and careful attention to details of fit.

The realization of the obvious inefficiency of correction techniques, that depend upon transmitting pressure through the entire hemithorax to the vertebral column, or in applying traction to the skull and mandible, has driven many surgeons to adopt a more direct operative approach to the problem.

Von Lackum and Smith (1933) performed what is apparently the first excision of a hemivertebra in lumbar scoliosis. Compere (1932) performed a similar procedure with excision of a hemivertebra in two cases with excellent correction achieved. He suggested anterior body fusion as a method of maintaining this correction. The development of kyphosis, however, has been a problem with this procedure, and this fact has been noted by Wiles (1951) and others.

More recently, Roaf (1955), Kazmin (1962) and Hodgson (1965) have recommended osteotomies of the vertebral bodies for the correction of idiopathic scoliosis. Roaf forms a closing wedge osteotomy on the convex side with removal of part of the rib and posterior elements, whereas, Hodgson performs an opening wedge osteotomy on the concave side, with anterior interbody fusion with autogenous strut grafts. In the author's personal experience with three procedures for the excision of hemivertebra, in one of which an anterior interbody fusion was performed, the magnitude of the surgery involved does not seem to lend itself to the casual vertebral surgeon.

INSTRUMENTATION

In 1955, Allan reported a series of 11 severe cases of scoliosis in which he had inserted a metal jack into the end of the transverse processes on the concave side of idiopathic curves. It was his impression that several objections existed to the technique, one of which was that only partial correction was possible, because the straighter the curve became, the less efficient the mechanical advantage of the jack. He did not feel the procedure was applicable to curvatures of less than 70 degrees. In 1957, Sevastikoglou performed a series of experiments on rabbits in an attempt to develop an elastic endoprosthesis to replace muscle. Because of the deterioration of rubber, he recommended stainless steel helical springs. Gruca subsequently published several papers on the technique of anterior and posterior alloplasty. It depended upon the attachment of springs to the transverse processes in the so-called posterior alloplasty, or, the pedicle in the anterior. In scoliosis of the second degree, i.e., 30 to 60 degrees, alloplasty was combined with a distraction device on the concave side, which was also spring loaded. In the more severe scoliosis deformities, wedge resection of the bodies, discs and processes, in conjunction with alloplasty and distraction, were required to achieve a satisfactory correction. More recently, Gruca has increased the force of the spring used in anterior alloplasty up to 40 to 50 kg (stretched to 60 % of their length). In 1961, Wenger reported 36 cases treated by the insertion of a turn-buckle jack through a direct intrathoracic paravertebral approach to the concave side of the curve. Wejsflog (1960) and Kazmin (1961) have also reported various distraction and contraction instruments for achieving correction. However, in 1962, Harrington reported over a decade of experience with the use of compression and distraction devices of his own design. The compression device is applied to the transverse processes on the concave side and the distraction device is inserted superiorly into the articular facet and inferiorly either into a notch cut into the lateral aspect of the interarticularis or the superior lamina. In a subsequent report (1963), Harrington stated that the correction by this technique was unmatched by any other system.

While still too early to assess the procedure, a very interesting approach to correction of the scoliotic deformity has been developed by Dwyer and Sherwood (1965). They achieved correction by thorough excision of the intervertebral disc, insertion of a bone block between the vertebrae, which is used as a fulcrum, and the insertion of screws into the vertebral bodies, through which a cable is positioned. Correction is then achieved individually following which the screw head is swaged to the cable. Finally,

further bone is added to complete an interbody fusion. The number of cases on which this procedure has been performed are to date few, and the follow-up brief, but the technique would appear to have merit. The copies of x-rays that Dwyer has made available to the author indicate excellent correction. However, as previously stated with reference to vertebral osteotomy and excision of hemivertebrae, the surgery required in this approach to the problem is extensive and may limit its applicability.

MAINTENANCE OF CORRECTION

The report of the Research Committee of the American Orthopedic Association in 1941, stated that correction without fusion resulted in a complete loss of correction after support was discontinued, in the majority of instances. In 1924, Hibbs reported the first 59 cases of scoliosis treated by spine fusion. Hibbs, Risser and Ferguson (1931) extended the concept of spine fusion as a method of maintaining correction. Unfortunately, though the principle may be excellent, it has been found that in practice a spine fusion in scoliosis is sometimes difficult to achieve. Smith (1958), in an editorial in the *Journal of Bone and Joint Surgery*, stated that in his opinion maintenance of corrections of 50 % is all that can be expected of spine fusion. In excess of this amount, fatigue fractures of the fusion can be anticipated. Similarly, Risser and Norquist (1958) believe that forcible correction of only twice the standing-recumbent x-ray difference should be anticipated and held.

Dissatisfaction with spine fusion has garnered added support from pulmonary function studies. Decreased vital capacity, total lung capacity and compliance are well established complications of scoliosis, particularly in those patients with spinal curvature which exceeded 45 degrees. Based upon such changes, it was anticipated that correction of scoliosis would produce improvement in the cardiopulmonary function. As reported by Erikson and Foss-Hauge (1963), however, there was no improvement in 41 patients they studied following treatment. Gucker (1962), referring only to his nonparalytic patients, found a net decrease of 9 % in pulmonary function following treatment. The best that might be expected, and this was in one patient only, was an equalizing of the preoperative vital capacity. This decrease in pulmonary function has been attributed to two causes. The first is the extended immobilization required by the spine fusion procedure, and the second is the probably frequent incorporation of the costotransverse joints in the fusion.

The Hibbs (1911) technique of posterior element spinal fusion has been widely adopted in the treatment of scoliosis. In most analyses of results, however, there are more modifications than original technique. The problem of pseudarthrosis prompted Moe (1961), in an editorial of the *Journal of Bone and Joint Surgery*, to write that experienced orthopedic surgeons were less concerned about methods of correction than with maintenance of the correction achieved. He stated, "There appears to be little doubt that a posterior fusion of sufficient length and of unquestioned integrity is necessary for the maintenance of permanent correction of a structural curve". Cobb (1948, 60) has also emphasized that the technique of fusion required destruction and bridging of the articular facets and the addition of fresh autogenous bone, if a satisfactory arthrodesis was to be achieved. Risser and Norquist (1958) note, as do many others, that pseudarthrosis is more common, the greater the degree of correction. They cite an overall pseudarthrosis rate of 15 %, and indicate that a solid fusion is more difficult to achieve in an older patient and in the more flexible parts of the spine. Alvik (1964) reported his pseudarthrosis rate as 6.2 % with correction of between 15 and 20 degrees by the Cobb technique. Riska (1964) reported a 13 % pseudarthrosis rate overall, the rate being 40 % in those patients in whom additional bone was not added and 32 % in those cases in which bank bone was added. In discussing the particular fusion techniques and results therefrom, he does not signify the methods and degrees of correction. Thompson and Ralston analysed the cases at the New York Orthopedic Hospital in 1949 and found an overall pseudarthrosis rate of 15.6 %.

In 1950, Ponseti and Friedman, studying the changes in the scoliotic spine after fusion, noted an initial lack of fusion in 68.3 % of their cases. Nineteen of fifty-two pseudarthroses closed spontaneously at the end of the growth period. They found loss of correction was often associated with visible deficiencies in the grafted area, but, in some cases, without obvious defects, progressive bending of the fusion mass occurred. On the basis of the very high pseudarthrosis rate reported, they concluded that neither lumbar nor double primary curves profited from surgical treatment. The problem of estimating the presence or absence of pseudarthrosis led to the assumption by Fielding and Waugh (1962) that any loss of correction in excess of 8 degrees by the Ferguson technique must be considered to be a pseudarthrosis. Others have approached this problem by routine exploration of the spine fusion (Outland, 1964), however, it is the author's observation that with a regular Hibbs fusion technique it is often very difficult to find a pseudarthrosis even when known to be present.

To reduce the pseudarthrosis incidence, Moe (1958, 61) has developed a

facet fusion technique with autogenous bone that has resulted in the lowering of his rate in idiopathic scoliosis to 7 %. The same problem has encouraged Cauchoix (1959) and Cotrel (1966) to use a rigid strut graft across the concavity of the primary curve.

From the many reports in the literature, it is apparent that a low pseudarthrosis rate following spine fusion in scoliosis depends not only upon a meticulous technique but the addition of fresh autogenous bone. Ponseti and Friedman found that postoperative immobilization of five months was beneficial. Several authors are of the opinion that excessive correction cannot be maintained. The studies from which this concept generated have largely been done with turn-buckle jackets, and it has probably been responsible, in a large measure, for the development of anti-gravity, the localizer and surcingle casts, as well as the postoperative use of the Milwaukee brace. Tambarino, Amburst and Moe (1964) concluded that the average correction and average loss was the same in their hands with the Harrington instrumentation procedure as with localizer casts, but they also noted a low incidence of pseudarthrosis. However, in Harrington's personally reported series, the results appear to be superior to those usually obtainable with conventional methods.

CURVE MEASUREMENT

It has been customary at the New York Orthopedic Hospital, since Ferguson developed his method of measuring scoliotic deformity, to record films by his method. This is perhaps unfortunate, because it is apparent that most orthopedic surgeons, for one reason or another, prefer the Lipman-Cobb technique, although, in our opinion, it has disadvantages. It would seem worthwhile to re-examine these two methods of measurement, and in so doing, perhaps it will be possible to shed some light on their relationship.

George and Rippstein have compared the two methods in 27 curves and calculated the average difference to be 25 %. Contrasting the correction achieved, they found 16 % greater correction when the Cobb technique was used for measurement. This is undoubtedly due to the increased correctability of the end vertebrae. These authors suggest, as still another method, the measurement of the distance of the apex from the line joining the two end vertebrae. Lusskin studied the two methods geometrically, assuming scoliotic curves to be the arcs of circles. In a comparison of the two techniques, he found 14.6 % difference, which indicated that

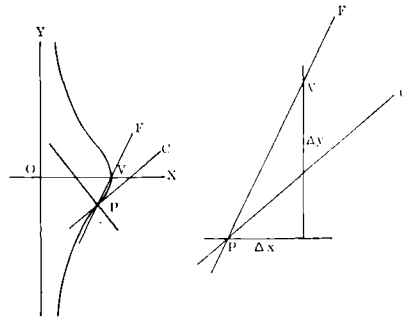


Fig. 1. *The Ferguson and Cobb methods of curve measurement are contrasted on a higher plane witch of Agnesi or versiera.*

the measurements by the Cobb technique were 1.41 times as great as those by the Ferguson.

It has been customary to refer to a scoliotic curve as either the arc of a circle, a parabola or a hyperbola. In reality, the most frequent single curve primary, with a superior and inferior compensatory curve, resembles a higher plane *witch of Agnesi* or *versiera*. This curve approaches the vertical axis asymptotically. One of the determinants of this curve is a circle the diameter of which is the distance between the asymptote and vertex. Thus, there would appear to be a geometrical basis for the suggestion of George and Rippstein, although it would be preferable to measure the curve by its displacement from the vertical axis rather than a line joining the two extremities. It is of some interest that orthopedic surgeons refer to the most deviated part of the curve as the "apex". In view of the more usual meaning of the word, the term "vertex" would be more accurate. In contrasting the Lipman-Cobb and Ferguson techniques of measurement, the former is formed by the angle of intersection of two normals to the curve, whereas the Ferguson represents the angle of intersection of two secants which pass through the vertex. Lusskin has stated that there is no linear relationship between these two measurements, and in fact,

this is true. However, it should be apparent that the limit of every secant is the tangent, which is, of course, perpendicular to the normal. Therefore, other things being equal, the secant will tend to approach the tangent as the limit of $\frac{\Delta x}{\Delta y}$ as Δx approaches 0, which is the definition of the derivative of y with respect to x .

CLINICAL EXPERIENCE

Since 1958, over 150 scoliotic patients have been surgically treated and followed by the author. Of these, the first 100 were followed a minimum of two years. The remainder, are excluded on the basis of the impossibility of evaluating the results of arthrodesis until the patient has been free of external support for at least one year.

Of these 100 patients, 77 were corrected postoperatively by the surcingle technique of Von Lackum. Eighteen were double primary curves, representing a total of 95 curves treated by the surcingle technique. Of the remaining 23 patients, 5 were corrected by turn-buckle jackets, 10 by concave rib resection followed by a correctional surcingle jacket, and 8 were corrected by spinal instrumentation (Harrington).

The surgical determinants followed have been:

1) *Rapid Progression*. It is considered important that serial x-rays, usually taken at intervals of three or four months, indicate progression of the disease, allowing for a 3 degree margin of error. This progression is assessed against a knowledge of the prognosis in the particular type of scoliosis.

2) *Lack of Balance*. Balance represents the ability of the patient to stand with the head centered over the midpoint of the pelvis. It is possible that lack of balance is associated with increased energy expenditure in both walking and standing.

3) *Pain*. Pain, as a surgical determinant, is unusual in the adolescent scoliotic, particularly in those with thoracic curvature. It tends to be more common in the older group and those with primary lumbar curves. In view of the high association of spondylolysis and spondylolisthesis with lumbar scoliosis, oblique x-rays were taken to recognize this cause of pain prior to any contemplated treatment. In very severe scoliotics, impingement of the ribs on the pelvis was often found to illicit pain. Thoracic pain, when present, tended to be a late complication of the deformity and was

characterized by either concave radiculitis, or was associated with osteoarthritis which often developed prematurely.

4) *Deformity*. Equal deformity is not a characteristic of equal curves. Thoracic scoliosis is more deforming than lumbar and double primary curves of the same degree. If examination of the patient indicates a marked deformity, it has been found that this tends to coincide with a measurement of at least 35 degrees (Ferguson) for thoracic and thoracolumbar curves, and 45 degrees for lumbar and double primary curves.

The value of standardization

In examining previously reported scoliosis studies, the author has found considerable difficulty in comparing correctional techniques. Obviously, while two curves may have equal measurements, the amount of correction that is achievable may be very different, and will depend upon the flexibility of the curve. Certainly, the difference between the erect and recumbent film gives some suggestion of this flexibility, and, bending films may also be helpful. However, the amount of correction obtainable on bending depends upon the zeal of the x-ray technician, and it has been

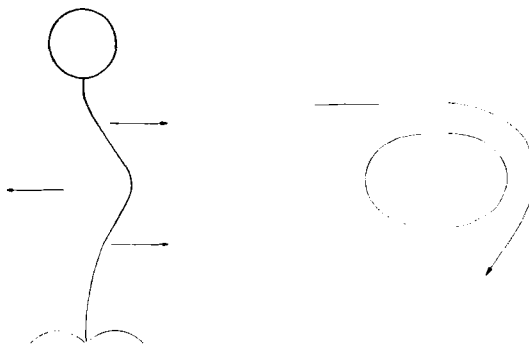


Fig. 2. *Illustration of the contralateral pressure system of correction in scoliosis.*

Fig. 3. *Method of achieving derotation at the apex of the curve.*

our finding that this is extremely variable between technicians. In order to circumvent this difficulty and establish a base line that would be truly significant, it has been my policy to obtain a maximally corrected film prior to any contemplated surgical procedure. In order to accomplish this, the patient was sedated and placed on a table developed by Von Lackum. This utilizes the surcingle system of contralateral pressures. The patient lies prone on a canvas belt which is supported at the neck and the groin. The areas for application of the surcingles are thickly padded with felt, and 15 cm-wide muslin bandages are looped about the body of the patient at those ribs which communicate with the apical vertebrae. This muslin is then secured by a ratchet. Two similar loops, in the case of a simple curve, are positioned at the ends and attached to ratchets on the opposite side of the table. The curve is then slowly corrected by tightening the ratchets up to the point of discomfort of the sedated patient. In the case of a right convex dorsal curve, as illustrated, the central loop pulls to the left, and the upper and lower loops pull to the right. In those patients where considerable rotation of the thorax exists, the apical surcingle is attached in the manner shown. This arrangement provides both lateral correction and derotation. The force on the apical surcingle is limited to about 50 kp by the muslin, which will tear with forces above this amount. The force tolerated by the patient is determined by the area of application. For the average adolescent scoliotic, this is about 375 cm², representing a maximal pressure of 0.13 kp/cm². Pressures above this figure produce marked patient discomfort and result in the development of pressure necrosis of skin.

One advantage of this simple method of correction is that the patient's body can readily be positioned so that alignment is achieved. The over-correction of secondary curves, which is seen with hinge turn-buckle jackets, is avoided.

A portable x-ray machine is positioned with the tube at the floor and the cassette applied to the dorsolumbar spine. No plaster jacket is put on at this time, and after verification of the x-ray, the surcingles are released. This film of the test correction, taken prior to surgery, has been used as a basis for comparison with final correction in plaster, if such is carried out by the surcingle technique, or by that obtained following one of the other methods of correction.

This test correction, or surcingle film, is used to evaluate the type of treatment best suited to the particular patient. As a close correlation exists (Fielding and Waugh, 1962) between this film and that obtainable following spinal arthrodesis, it is clearly possible to anticipate what may be expected from conservative correction technique. If the test x-ray

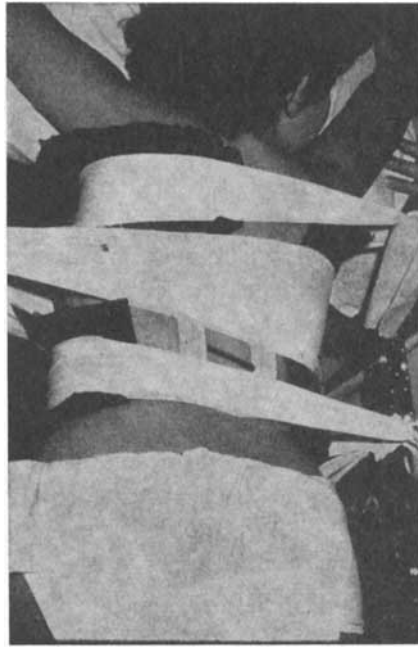


Fig. 4. Method of placing surcingles for correctional test roentgenogram. The patient has a right dorsal scoliosis deformity.

revealed a curvature of 20 degrees or below (Ferguson), then it was not believed desirable to incur the added risks of extra surgery. If, however, the amount of correction was not considered adequate, concave rib resection (Flinchum, 1963) was carried out in addition to spinal arthrodesis, in those patients who, by the excursion of their iliac apophyses and bone age, were considered to have two or more years of growth remaining. However, patients in this same category, without significant growth remaining, underwent a Harrington instrumentation correction and arthrodesis.

We have performed bilateral spine fusions by the Hibbs technique through a straight mid-line incision, care being taken in opening the wound, to perform as clean a subperiosteal dissection as possible in the hope of preserving an osteogenic layer over the bone grafts. Generally, cartilage is not removed from the thoracic facets, but is in the lumbar area; in using a gouge on the interarticularis, however, no attempt is made to preserve the region of the facet.

Considerable problem has arisen in the past as to the most desirable extent of the fusion procedure. Two extremes have been represented by those who recommended fusing only the primary curve and those surgeons who recommended fusing between parallel vertebrae. Based upon empirical observations, the following routine has been adopted: the primary or major deforming curve is fused with one additional vertebra below for each year of growth remaining. As a result, it has not been necessary to extend any fusion because of inadequate length since 1958.

In this series of 100 cases, there were 189 spine fusion procedures. Four to eight vertebrae were usually fused per stage. Twelve fusions were carried out in one stage, 75 in two stages, and, 9 in three stages. The total coverage varied from 6 to 14 vertebrae with an average of 10.

Graft material

In 69 of the operative procedures, homologous bone was supplemented to the locally available autogenous bone. In 110 stages, autogenous bone was added which was removed from the posterior iliac crest either through a separate or a mid-line extension of the spine fusion incision. Processed calf bone (Squibb) was added in 8 procedures, and no additional bone besides that locally available in two operations.

Postoperative management

It has been our policy to place all patients in a postoperative surcingle jacket. In those patients on whom a spinal instrumentation procedure had been carried out, the pressure applied to the surcingles was enough to secure a snug well-fitting cast, but there was no attempt to relieve pressure on the instrument by external force. It seems desirable that the plaster be retained for a *minimum* of nine months. During this interval, the patient is kept recumbent for the first three months, maximum elevation of 25 degrees being permitted for the head of the bed. In the second three-month period, bathroom privileges are allowed once a day and in the final three-month period, progressive ambulation. At nine months, the patient is readmitted to the hospital for removal of jacket and x-rays. After being out of plaster for 24—36 hours, the spine is carefully re-examined clinically. Areas of tenderness are correlated with the radiological examination. If the x-ray indicates an immature area in the fusion, or the patient's tenderness is persistent, particularly with reference to the apical area or the junction of stages, a new surcingle correctional jackets is applied for an

additional three-month period, at the end of which time the patient is readmitted and re-evaluated. In the great majority of patients, we find the fusion mass is mature, and there is no tenderness on deep palpation. These children are allowed to ambulate about the hospital ward, and as soon as this can be accomplished satisfactorily, usually in one day, they are discharged from the hospital with strict instructions to remain at home and not participate in any form of athletics whatsoever. On return to the out-patient department, in six weeks, clinical and radiological evaluation is carried out once again, with particular reference to any loss or correction or difference between the erect and recumbent films. If a loss of correction does occur, the patient is then readmitted to the hospital and a decision made as to whether a further period in plaster, or, repair of a pseudarthrosis is indicated. Subsequent re-examinations are carried out at three-month intervals during the first year, six-month intervals during the second year, and yearly intervals thereafter.

End result evaluation

One of the major problems in orthopedic assessment is the determination of improvement in the patient's condition. In any disease, such as scoliosis where cosmesis plays such an important role, it is doubtful that several independent evaluators could reach identical conclusions; but there is little doubt, that most failures of treatment are due to loss of correction. For this reason, we have tended to make the arbitrary assumption that an 8 degree loss of correction represents an unsatisfactory result, and possibly, a pseudarthrosis (Fielding and Waugh, 1962). Some of this 8 degrees is the margin of error in x-ray measurement, and part, the accommodation of the soft tissues to the pressure of the jacket. In the spine instrumentation procedure, erosion of bone may be a factor due to the pressure generated by the distraction hooks.

In evaluating the four correctional techniques we have used, it was apparent that the concave rib resection technique of Flinckum (1963) permitted little increase in postoperative correction. Measurement of the gap created in the posterior ribs by segmental resection indicated that when the surcingle technique of correction was used, the spine moved towards the concave side. This might in turn cause a further decrease in vital capacity.

In comparing correction achieved with the hinge turn-buckle jacket and the instrumentation procedure of Harrington, it was found that approximately similar degrees of correction are obtained below the surcingle test film (mean of 20 degrees and 17 degrees, respectively). However, as

we have employed it, the end result has generally been less satisfactory with the hinge turn-buckle jacket. This is attributed to the rather considerable loss of correction (mean of 14 degrees) that occurred with removal of the turn-buckle jacket and replacement by a surcingle jacket. Risser (1964) has stated that, in his opinion, greater correction might be achieved by removing the turn-buckle jacket and applying a localizer cast. It might be argued that Risser's technique has not been followed, however, it is the author's feeling that the differences in correction obtained by a localizer and surcingle jacket are slight. Many authors have remarked about the potential dangers of the turn-buckle jacket with respect to the secondary curves. Certainly, with the final application of either a localizer or surcingle jacket this hazard is removed.

In every spine instrumentation procedure the author has performed, including those which have not been followed for two years postoperatively, the question did arise as to how much force could be safely applied to the hooks without risk of their "cutting out". In two resistant curves, the fact that this occurred with the distraction device, necessitated, in one patient, replacement of the superior hook at a higher level, and, in the other, a complete loss of correction postoperatively required salvage by a correctional plaster jacket.

With the application of a snug surcingle jacket following the procedure, our net loss (excluding the failure above) has been only 5 degrees. However, in those patients on whom we have chosen to use the Harrington procedure, the amount of correction obtained has never been as much as might have been desired. A final average curvature of 33 degrees in seven patients still represents a moderate amount of deformity. The same thing can, of course, also be said about the turn-buckle jacket method of treatment. Tambarino, Ambrust and Moe (1964) concluded that their average correction and loss with the Harrington procedure was similar to that obtained with plaster. The results referred to in this series could offer substantiation of their assertion.

In the literature on scoliosis, the definition of pseudarthrosis is far from standardized. Most of those reporting on this problem list their own criteria which often contain a large subjective element. As previously noted, it has been our policy to classify all cases that lose more than 8 degrees as an unsatisfactory result. It is the author's belief that this usually indicates a pseudarthrosis. The infrequent necessities for pseudarthrosis repair suggested that many cases given time and loss of correction go on to fuse spontaneously. This is in agreement with the results reported by Ponseti and Friedman (1950). Discussing factors that pertain to the achievement of a solid fusion, Risser and Norquist (1958) have noted that

high degrees of correction are more likely to be associated with an increased incidence of pseudarthrosis, and this we have also found to be true. Analysis of loss of correction with respect to type of bone added at the arthrodesis procedure has been most illuminating. In those patients who had only bank bone added during all stages of fusion, our failure rate was 50 %. This is contrasted with a figure of 16 % in those who had only autogenous bone added, the overall rate being 28 % with loss of 8 degrees correction.

The issues raised appear to substantiate the two-fold nature of the scoliosis problem. One of these is the frequent failure to achieve correction, which is, of course, closely linked to the difficulties of maintenance. The ultimate goal of treatment is today, as in the past, the prevention of scoliosis development. However, in those patients with an established deformity, it would be desirable to attain and maintain a straight spine were this within the limits of complete safety.

III Extravital experimentation

In the previous section dealing with the surgical treatment of idiopathic scoliosis as employed by the author and other surgeons, it is apparent that the amount of correction obtainable, while dependent on many factors, is usually in the range of 40 % to 60 %, of which less is secured as an end result. The limiting factor with external correction has usually been the pressure tolerance of the skin and presumably the limiting factor with spinal instrumentation is most frequently the strength of the posterior elements. Attempts have been made to evaluate these structures, but the few available reports are vague and incomplete. For this reason, it was believed that improvement in the effectiveness of spinal instrumentation required an accurate study of various methods of attachment to the posterior elements.

METHOD AND MATERIAL

Instrumentation Hooks

The types of hooks commercially available for instrumentation procedures are constructed of stainless steel. The entire series of Harrington hooks are made in the shape of a semi-circle of radius 4.8 mm. However, the



Fig. 5. Lateral illustration contrasting molded, Gruca, Zimmer No. 1251, and machined (Thoracic) hooks.

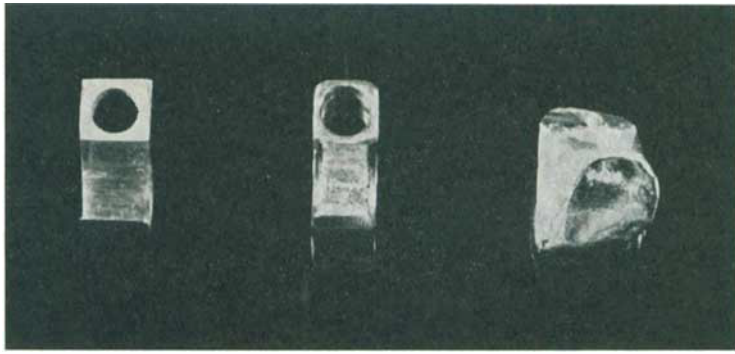


Fig. 6. *Front view of machined (thoracic), Zimmer No. 1251, and molded hooks.*

width varies from 5.6 mm to 9.0 mm. The Gruca alloplasty hook has an angular shape of approximately 65 degrees and measures 3 mm in width. Neither of these types conform to the anatomy to which they are applied, which raises the question of stress concentration. In order to evaluate the possible advantages of a more anatomical design, 25 thoracic and lumbar spines were examined from children and adults. Wax models were then prepared, which, by suitable alteration, became fairly universal in their applicability to these vertebrae. It was found that the anatomical differences between the thoracic and lumbar spines were so great, that it was necessary to develop two separate hooks. The thoracic was acutely angled at 50 degrees and measured 10 mm in width. The lumbar hook, for attachment to the superior lamina was semi-circular in shape with a diameter of 8 mm and was 10 mm in width. This hook obviously closely

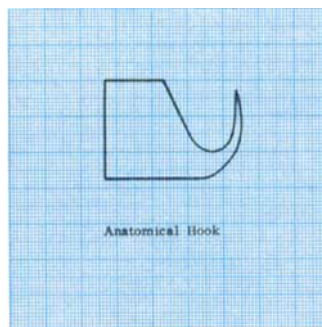


Fig. 7. *Design of machined hook, thoracic.*

resembled the Harrington. The wax models were then cast in vitalium and polished in preparation for testing. As the design of both of these hooks could be further altered into a more regular shape, a series of hooks were machined of stainless steel (Sandviken, Sweden, 6R60).

Methyl methacrylate

Examination of the hook attachments to the vertebral column indicated that, while it had been possible to change the design to fit more anatomically, the total surface area of the attachments had been increased very little. In order to create a far larger surface area, various techniques of fabricating an individual mold of the posterior elements were explored. Many forms of plastic material are produced, but very few have been adequately investigated with respect to their toxicity in the body. After exploring several varieties, it was finally concluded that self-curing methyl methacrylate, while having some undesirable characteristics, was of adequate strength and easily handled. Preliminary investigation was then carried out of this material from the point of view of its usefulness in making a mold of the posterior elements during a possible instrumentation procedure. Wiltse, Hall and Stenehjem (1957) previously investigated the experimental possibilities of using this material. However, performing spine fusions with wire reinforcement of four vertebrae in rabbits, necrosis of the adjacent bone, in particular the spinous processes developed. This they attributed to the high temperature of polymerization. By inserting thermocouples at the junction of the femur and the methyl methacrylate at the time of polymerization, they had recorded temperatures of 80 degrees C. They had also suggested that ice water might be used to lower this temperature.

The amount of material that would be necessary to form a satisfactory mold of the posterior elements of one vertebra was determined to be 15 grams of polymerized material, which without cooling, developed internal temperatures of 120 degrees C at the height of polymerization. The most satisfactory solution to the achievement of low temperature polymerization within an operatively feasible length of time, was established using 10 grams of polymethyl methacrylate powder containing a small amount of benzoyl peroxide and 5 ml of methyl methacrylate monomer containing dimethyl p-toluidine. The polymer may be gas sterilized and the monomer is self-sterilizing. A "heat-sink" of stainless steel which measured 20 mm in length and 10 mm in diameter was introduced. This could be machined

to accept any desired type of instrument. Following the mixing of the materials, the entire area was continuously irrigated with a 20 degrees C. solution of normal saline. With this technique, polymerization occurred in an average of 22 minutes following mixing with a maximum temperature of 42 degrees C. recorded at multiple points in the material.

Evaluation of the surface area available for an acrylic mold was made by applying soft sheets of moulding wax unilaterally to a series of thoracic and lumbar vertebrae. These molds were then flattened and traced on paper, the area of which was measured with an Amsler Planimeter to an accuracy of 0.1 cm². The mean area obtained for the lumbar spine was 14.2 cm² (s=4.38) and for the thoracic 8.6 cm² (s=1.11). These figures, using the same technique of measurement, were compared with a Harrington hook (Zimmer No. 1253) which had a surface area of 2.2 cm², Gruca 1.0 cm² and the machined anatomical hook with an area of 2.4 cm².

Experimental apparatus

The following loading tests were carried out in an Amsler materials testing machine with a spring calibrated to 500 kp. The predetermined inaccuracy

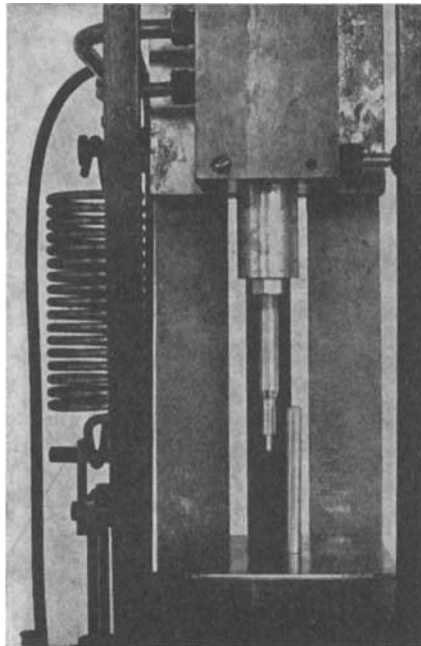


Fig. 8. *Amsler Materials Testing Machine with testing stage in place prior to placement of specimen.*

of the machine at 50 kp and above was less than 1 %. A steel rod was attached to the permanently mounted stage and to this each variety of hook, as well as the metallic insert of the acrylic could be attached. Each specimen was mounted on the moveable stage. Because of lateral bending of the specimen, it was necessary to stabilize the spinal segments by a longitudinally placed rod through the neural canal. The load applied and linear displacement of the hooks were recorded. The thoracic and lumbar spines were tested separately. Gross pathological examination and radiological study in the AP and lateral views was carried out of all specimens to eliminate intrinsic vertebral pathology. Those spines in which there was a suggestion of disease were eliminated from the series.

Material

This experimental study was carried out on 141 vertebrae obtained from 35 samples of human lumbar and thoracic spines, obtained from 22 autopsy subjects. The pertinent clinical information for each patient is listed.

AUTOPSY MATERIAL

Test Number	Autopsy Number	Age Sex	Wt kg	Time in Hospital	Death To Testing	Cause of Death
1	I 487	68M	98,8	59 days	2 days	Myelofibrosis
2	I 500	69M	48,7	1 day	1 day	Gastric Carcinoma
3	I 504	80F	—	3 days	2 days	Myocardial Infarction
4	V 197	19M	—	0	4 days	Head Injury, Laceration of Bowel
5	I 525	62M	—	12 hrs	3 days	Pulmonary Embolism
6	I 531	57M	—	12 hrs	1 day	Myocardial Infarction
7	I 581	64M	180,1	7 days	1 day	Uremia
8	V 208	19M	—	0	2 days	Skull Fracture, Abdominal Hemorrhage
9	I 558	79F	—	19 days	3 days	Pneumonia
10	II 124	40M	—	12 hrs	1 day	Gastro-Intestinal Bleeding
11	I 717	58M	—	38 days	8 hrs	Pancreatic Necrosis, Carcinoma of Prostate
12	I 721	73M	—	7 days	8 hrs	Pulmonary Embolism
13	I 732	70M	—	1 day	8 hrs	Pancreatitis, Thrombosis Basilar Artery
14	I 872	54F	—	17 days	2 days	Cerebral Hemorrhage
15	I 869	50M	—	4 days	2 days	Congestive Heart Failure
16	I 906	62F	—	1 day	1 day	Congestive Heart Failure
17	I 925	62M	58,1	16 days	1 day	Congestive Heart Failure
18	V 206	6M	—	0	1 day	Drowning
19	V 207	4M	—	0	3 days	Head Injury
20	V 213	16F	—	0	1 day	Head Injury
21	V 221	11M	—	0	2 days	Laceration Liver
22	I 578	62F	63,2	32 days	4 days	Peritonitis

Efforts were made to exclude specimens that might have generalized bone disease or metastases. It was not possible to exclude all cases of osteoporosis or osteoarthritis, and in fact, because of the application to scoliosis, this was not felt to be necessarily desirable. Every effort was made to obtain specimens in the scoliotic age group, but this obviously proved difficult. In order to circumvent the problems of storage, all tests were carried out immediately after a specimen was received. This was usually within one and never more than two hours after the autopsy was performed.

Preparation of the specimen

The majority of specimens were obtained from the Department of Pathology, Sahlgrenska Hospital. In those patients where the cause of death was traumatic, the specimens were obtained from Vasa Hospital. In general, the entire thoracic and lumbar spine was removed, including the upper part of the sacrum. In some cases, for various reasons, only the thoracic spine was available. These were used for a separate series of comparison tests. When the entire spine was available, thoracic and lumbar were separated through the 12th thoracic vertebra in order to

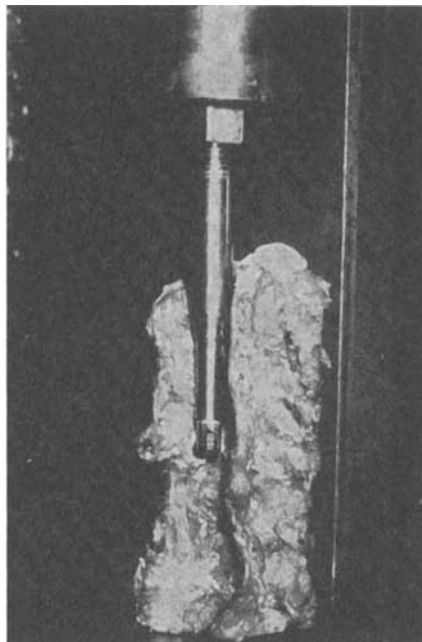


Fig. 9. Specimen of lumbar spine with Zimmer No. 1251 hook inserted into superior lamina.

facilitate handling on insertion into the testing machine. The posterior elements were cleared by subperiosteal dissection as would be done in a spine fusion procedure. Those vertebrae which were to be used to determine the strength of the pedicle had a lateral dissection carried out to provide exposure of this region.

The sites for the various attachments were identified from a predetermined randomized list and the specific recommendations for each operative technique followed relative to the insertion of the particular method of attachment. (Harrington, 1964, Gruca, 1962) Because of structural weakness of the commercially available alloplasty hooks, these failed before the pedicle. Accordingly, a stronger hook of the same internal dimensions was fabricated in order to allow testing of the pedicle to failure (Sandviken, Sweden, 6R60).

A site for the application of acrylic was carefully cleaned of soft tissue in an attempt to provide as much loading area as possible. This was done by removing the superficial layer of the ligamentum flavum and a part of the interspinous ligaments. It was found that a small hole drilled in the interarticularis with undercut edges greatly reinforced the attachment of the acrylic. After mixing the monomer and polymer and pouring the



Fig. 10. Placement of Gruca hook on transverse process as in posterior alloplasty position.

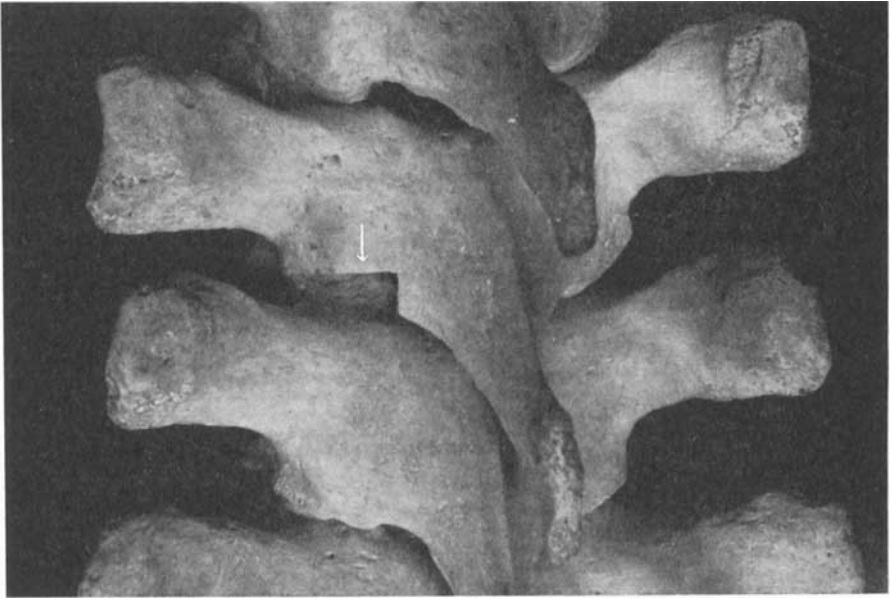


Fig. 11. *Purchase site for thoracic hook into inferior facet.*



Fig. 12. *Superior hook in place on thoracic spine (Harrington).*

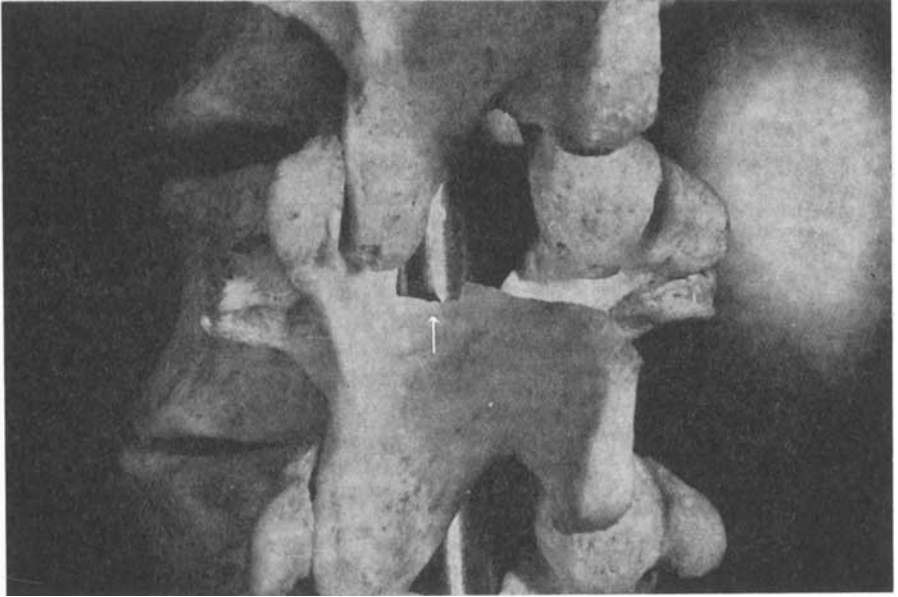


Fig. 13. *Purchase site for lumbar hook in superior lamina.*

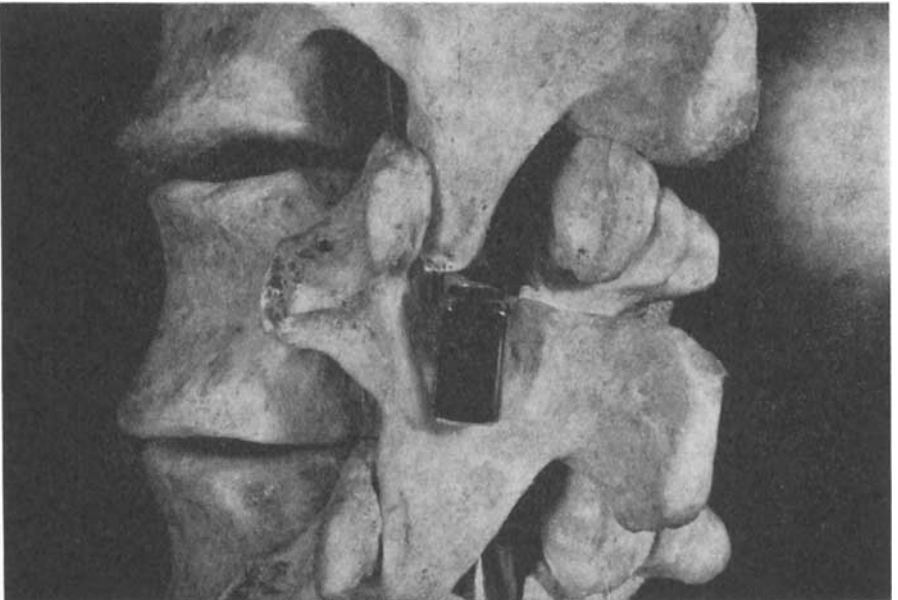


Fig. 14. *Inferior hook in place on lumbar spine (Harrington).*



Fig. 15. *Placement of Gruca hook on pedicle as in anterior alloplasty position.*

plastic into position on the vertebra, the metallic insert was carefully placed to permit the application of force in the longitudinal axis of the spine. Unless this were done with some care, the acrylic levered off the lamina with the application of relatively little force. This would be of some significance in any clinical application of the material to the posterior elements, and it suggested a method by which the material could be removed if such proved necessary.

Animal experiments

In order to ascertain whether the heat of polymerization was responsible for the bone necrosis reported by Wiltse, Hall and Stenehjern (1957), three dogs and two cats were utilized for the implantation of 10 grams of polymer and 5 ml of monomer. The material was placed on the cleaned posterior elements of the spine. A piece of stainless steel (Sandviken, Sweden, 6R60) was implanted in the center of the acrylic, and this was cooled during polymerization by constant irrigation with 20 degrees C. saline. At another location, a small wire marker was inserted, but no

attempt was made to retard polymerization or lower the temperature at which this occurred. These animals were examined regularly thereafter and sacrificed at 5 days, one month, and five months. A complete autopsy was performed on the first dog on the sixth day post-implantation to determine the presence or absence of any signs of toxicity in the lungs, liver and kidneys that could be attributed to the free monomer. No such changes were determined to be present. The remaining two dogs and two cats were examined radiologically to determine whether necrosis of the posterior elements had developed. Examination by this technique failed to indicate any changes in either the spinous or transverse processes, nor was there any alteration in the laminae.

Autopsy performed on the animals confirmed that a low-grade infection had developed in one cat resulting in the expulsion of the cooled polymer

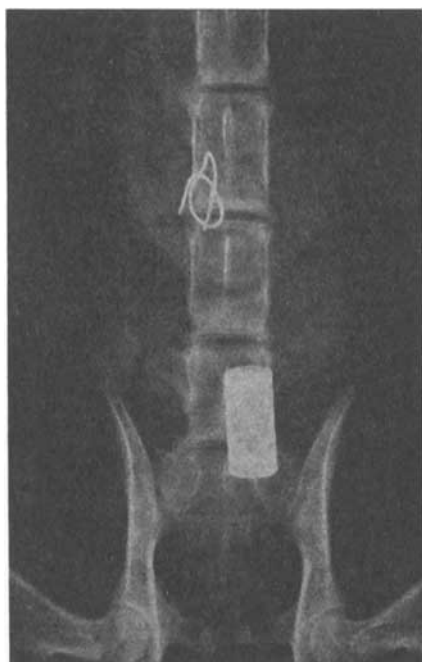


Fig. 16. *Roentgenogram of Cat No. 2. showing position of methyl methacrylate as indicated by metallic markers.*

and retention of the uncooled. This plastic material was exposed at the bottom of a sinous tract which measured approximately 2 cm in its greatest diameter. The remaining animals showed no untoward reaction. In all cases, the plastic material was easily removed. In fact, in most cases it was definitely loose, particularly at five months. Grossly, there was found to be a thin connective tissue membrane in relationship to the material, but beyond this, surrounding tissue appeared normal. The bone, next to the plastic, was covered with a thin layer of periosteal-like tissue, although periosteum had been stripped at the time of insertion. The bone itself appeared completely unremarkable and there was no gross evidence of injury to the spinous and transverse processes. As far as could be determined, there was no difference between the cooled and uncooled polymer.

Results of animal implantation

	Sacrificed Days Post Implantation	X-Ray	Pathological Examination
Dog 1	5	Neg	No evidence of toxic degeneration of lungs, liver, or kidneys
Dog 2	30	Neg	No significant foreign body reaction or bone necrosis
Dog 3	150	Neg	No significant foreign body reaction or bone necrosis
Cat 1	150	Extrusion of cooled acrylic	Chronic draining sinus to polymer. Associated scar tissue
Cat 2	150	Neg	No significant foreign body reaction or bone necrosis

Microscopic examination was carried out of soft tissue and bone stained with hemotoxylin and eosin. The microscopic findings served to reinforce the gross examination. There was no demonstrable evidence of injury to the posterior elements, and the lacunae contained apparently normal osteocytes.

RESULTS

Static tests were performed in three test sequences.

In Table 1, the Harrington, Gruca and acrylic techniques of attachment are generally compared once in the thoracic and lumbar specimens in a random sequence. The thoracic spine was tested inverted for the Harrington and acrylic methods of attachment. Similarly, the lumbar spine was inverted to test the Gruca technique. In all cases, the Harrington and acrylic attachments were performed on the left side of the specimen, (as would be more common in idiopathic scoliosis), and the Gruca on the right. While important, the point at which failure was noted to have begun (*Relative failure*) was not always accurately determinable and has been indicated as such by parentheses. Failure of the Gruca hook itself before the pedicle is indicated by an asterisk.



Fig. 17. Gruca hooks that failed are shown on right and left with a regular hook in the center for comparison.

Table I
TESTING SEQUENCE OF SCOLIOSIS ATTACHMENTS
TO RELATIVE AND COMPLETE FAILURE

Number	I-487	I-500	I-504	V-197	I-525	I-531	I-581	V-208	I-558	I1-124
Thoracic										
Acrylic	T4-(195)/200	T5-(280)/280	T5-174/189	T4-(285)/400 +	T5-(290)/302	T5-178/325	T6-(186)/241	T4-(180)/184	T4-160/200	T4-(170)/175
Gruca Ant. ¹		T6-(70)/70, 62*	T4-38/42	T5-27/47	T4-20/38	T6-80/95	T4-65/68	T4-80/91	T5-(74)/76	T6-(95)/110
Gruca Post. ²	T8-(20)/25	T6-57/62	T6-(50)/55	T6-80/87	T6-62/92	T4-105/125	T5-80/95	T5-72/84	T6-(100)/111	T5-109/134
Harrington ³	T4-(35)/87	T4-45/50								
Lumbar										
Acrylic	L2-150/204	L1-400 + /400 +	L3-(290)/310	L1-400 + /400 +	L1-(250)/283	L3-320/325	L1-350/360	L2-(250)/255	L3-(303)/303	L3-400 + /400 +
Gruca Ant.		L2-50*, 66*	L2-62*			L1-(150)/156	L3-(183)/188	L4-(54)/59	L2-60/62	L2-328/348
Gruca Post.	L1-(35)/40		L2-20/25	L2-25/29	L3-47/67	L2-(193)/198	L2-182/217	L3-85/189	L1-40/55	L1-180/270
Harrington ⁴	L3-(140)/153	L3-(106)/125	L1-(115)/120	L3-234/259	L2-165/185					

+ Indicates in excess of

* Indicates failure of hook

() Indicates estimate of relative failure

¹ Gruca Anterior refers to pedicle attachment

² Gruca Posterior refers to transverse process attachment

³ Zimmer No. 1253

⁴ Zimmer No. 1260, small hole

Table II
 TESTING SEQUENCE TO COMPLETE FAILURE OF
 HARRINGTON & "ANATOMICAL" (MACHINED) HOOKS
 ON THE THORACIC SPINE

Number	I-717		I-721		I-732		I-872		I-869		I-906		I-925	
Device	H ¹	An	H ¹	An	H ¹	An	H ¹	An	H ¹	An	H ¹	An	H ¹	An
	115	120	167	290	122	180	94	159	172	166	56	118	144	165
	66	134	267	197	200	245	103	113	211	196	103	126	142	172
	74	110	153	130	211	240	86	112	282	257	87	87	170	170
	40	147	137	114	134	242	47	115	269	292	144	155	165	207
			200	254			87	103	171	217	168	145	273	247
			173	174										

¹ Zimmer No. 1253

Table III
TESTING SEQUENCE OF SCOLIOSIS ATTACHMENTS
TO RELATIVE AND COMPLETE FAILURE IN CHILDREN

Aut. No.	1A V-206	1G —	1H ¹ —	2A V-207	2G —	2H ¹ —	3A V-213	3G —	3H ¹ —	4A V-221	4G —	4H ¹ —
Thoracic												
1												
2												
3	144/189				(44)/47A	(25)/28		60/66P (62)/67A	(103)/106		(58)/62A	
4		(32)/36A	28/53		25/33A	16/19	173/186	55/64P 82/90A	70/76		(67)/71A (74)/79A	30/54 (47)/50 80/86
5	(165)/175		42/57			(25)/28		(55)/57P 85/100A 45/62P	130/137	(136)/136	(55)/58A 115/123A	(67)/69 33/48
6		15/37A						140/153A				
7												
8		(45)/47A	(58)/61		(64)/67A		(275)/280		(105)/108			
9	100/150 +	(50)/52A 40/48A	32/40	120/148	62/68A	22/37				190/269		
10	155/214											
11												
12												
Lumbar												
1	145/152		80/95	123/138		74/84	(190)/190	156/174A	(118)/118			(105)/110
2	(95)/96	86/96A	(44)/47			25/35	270/277	(46)/50P 62/87A	(108)/110	(220)/220	125/132A	40/81
3	(100)/108							(25)/25P	170/179		130/144A	140/169
4		(60)/64A			(20)/23A (20)/22A							
5												

+ Indicates in excess of

() Indicates estimate of relative failure

A Anterior attachment (pedicle)

P Posterior attachment (transverse process)

¹ Thoracic - Zimmer No. 1253

Lumbar - Zimmer No. 1260, small hole

Test Number 7
 Autopsy Number I-581 64 M.
 Died 28/4/66 Tested 29/4/66
 Random Sequence T AHG: L AHG

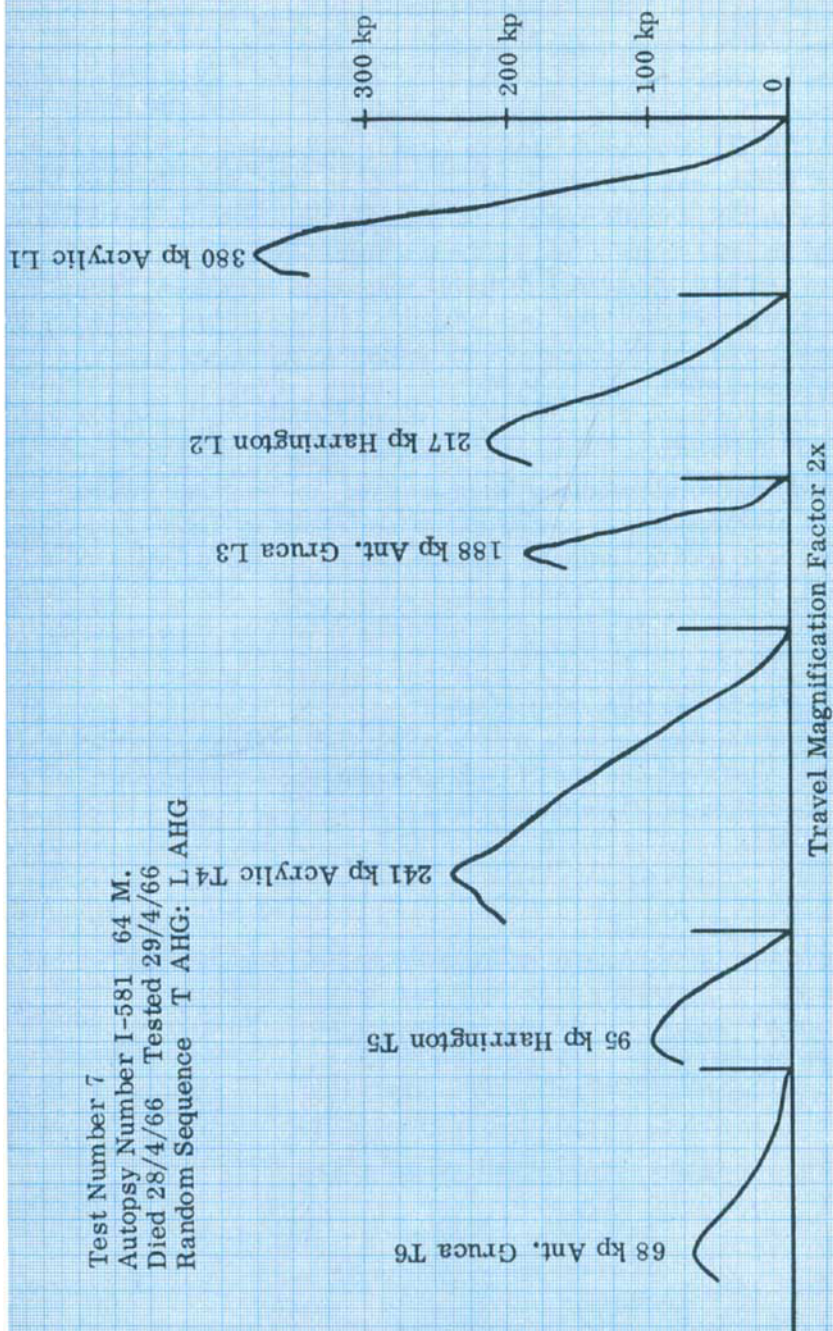


Fig. 18. Reproduction of a testing sequence (I-581, Table I).

In the second test sequence (TABLE II,) the Harrington and "anatomical" hooks are compared on different sides of the same thoracic vertebrae, the choice of side and which was performed first, was by predetermined random sequence. No attempt was made to ascertain relative failure in this series. The specimens were tested inverted.

In TABLE III, are shown tests to relative and complete failure of the acrylic, Gruca and Harrington attachments to specimens obtained from children in the scoliotic age group. Multiple tests were performed in a random sequence as permitted by the specimen. When the performance of a given test was considered to have jeopardized subsequent testing by injury to the vertebra, the next available intact vertebra was selected. The position of the attachments with respect to specimens were as listed in the first sequence.

Statistical analysis

Standard statistical methods were utilized to evaluate results. An analysis of variance was carried out of the results in Tables I and III. A t-test was used to estimate the significance of the paired results in Table II.

Table I

1. Complete failure load, thoracic, adults

For each of the four methods, A (=acrylic), G.A (=Gruca, anterior), G.P (=Gruca, posterior) and H (=Harrington) the mean complete failure loads are calculated. These means are as follows:

Method	A	G.A	G.P	H
Mean	249.6	85.0	42.8	87.0
n	10	6	5	10

A simple analysis of variance indicates significant inequality of the means.

Source of Variation	d.f.	Sum of Squares	Mean Squares	F
Between means	3	211585	70528	30.8
Within groups	27	61813	2289	
Total	30	273398		

The following are the differences between means:

	A	G.A	G.P	H
A		164.6*	206.8*	162.6*
G.A			42.6	-2.0
G.P				-44.2

* Significant difference

In analysing the differences by calculating 95 % confidence limits for corresponding orthogonal contrasts (Scheffé, 1953), it is seen that the acrylic method of attachment gives a significantly higher mean complete failure load than any other, and also, that there are no significant differences between other methods.

2. Relative failure load, thoracic, adults

Similarly, the following means are calculated:

Method	A	G.A	G.P	H
Mean	209.8	77.3	32.4	73.8
n	10	6	5	10

The analysis of variance indicates significant inequality.

Source of Variation	d.f.	Sum of Squares	Mean Squares	F
Between means	3	149129	49710	45.8
Within groups	27	29302	1085	
Total	30	178431		

The differences between means are as follows:

	A	G.A	G.P	H
A		132.5*	177.4*	136.0*
G.A			44.9	3.5
G.P				-41.4

* Significant difference

3. Complete failure load, lumbar, adults

The following means are calculated:

Method	A	G.A	G.P	H
Mean	326.0	162.6	40.3	175.1
n	10	5	4	10

The analysis of variance indicates significant inequality.

Source of Variation	d.f.	Sum of Squares	Mean Squares	F
Between means	3	272853	90951	16.4
Within groups	25	137814	5513	
Total	28	410667		

The differences between means are as follows:

	A	G.A	G.P	H
A		163.5*	285.7*	150.9*
G.A			122.3	-12.5
G.P				-134.8*

* Significant difference

It is noted that in addition to the values for the acrylic method of attachment being significantly higher than the other methods, the Harrington is significantly higher than the Gruca hook when attached to the transverse processes of adult lumbar vertebrae.

4. *Relative failure, lumbar, adults*

The following means are calculated.

Method	A	G.A	G.P	H
Mean	311.3	155.0	31.8	143.9
n	10	5	4	10

The analysis of variance indicates significant inequality.

Source of Variation	d.f.	Sum of Squares	Mean Squares	F
Between means	3	274578	91526	16.3
Within groups	25	139980	55992	
Total	28	414558		
A	156.3*	279.5*	167.4*	
G.A		123.2	—11.1	
G.P			—112.1	

* Significant difference

Table II

A t-test of the mean of the paired differences shows that the "anatomical" hook method of attachment to the thoracic spine gave a significantly higher mean complete failure load than the Zimmer No. 1253. The calculated difference with $n=34$ is 32.5 ± 6.4 ($t. = -5.07$).

Table III

Because of the small number of autopsy specimens, the thoracic and lumbar figures were not separated. The method used for testing significance was otherwise the same as in Table I.

I. *Complete failure load, thoracic and lumbar, children*

The following means are calculated:

Method	A	G.A	G.P	H
Mean	182.9	75.9	52.3	77.2
n	16	26	6	27

The analysis of variance indicates significant inequality.

Source of Variation	d.f.	Sum of Squares	Mean Squares	F
Between means	3	152066	50689	26.2
Within groups	71	137566	1938	
Total	74	289632		

The differences between means are as follows:

	A	G.A	G.P	H
A		107.0*	130.6*	105.7*
G.A			23.6	—1.3
G.P				—24.9

* Significant difference

2. Relative failure load, thoracic and lumbar, children

The following means are calculated:

Method	A	G.A	G.P	H
Mean	162.6	68.2	47.7	67.3
n	16	26	6	27

The analysis of variance indicates significant inequality.

Source of Variation	d.f.	Sum of Squares	Mean Squares	F
Between means	3	120250	40083	21.9
Within groups	71	129700	1827	
Total	74			

The differences between means are as follows:

	A	G.A	G.P	H
A		94.4*	114.9*	95.3*
G.A			20.5	0.9
G.P				—19.6

* Significant difference

DISCUSSION

The results obtained indicate that a greater vertical load may be applied to the posterior elements of thoracic and lumbar vertebrae using a mold of methyl methacrylate than with conventional methods of application (hooks). The difference of the means was statistically significant.

All methods of attachment to the lumbar vertebrae, except for the attachment of the Gruca hook to the transverse processes, gave mean failures of over 140 kp (complete) and 120 kp (relative). In the thoracic region,

however, the means failures were consistently lower, being 87 kp and 74 kp (complete and relative) for the Harrington and 84 kp and 78 kp for the Gruca inserted in the pedicle.

The mean figures obtained by attachment of the Gruca hook to the transverse processes are lower than by any other technique.

Although the surface area of the hook designed for experimental testing was only 9 % greater than the Zimmer No. 1253, the mean failure values were 20 % higher. This difference was found to be statistically significant.

A method was developed for measuring the surface area of application of all attachments. The results obtained by this method indicated greatly increased areas of application for the acrylic, particularly on lumbar vertebrae. However, the measured areas of application did not correspond to the actual area of pressure application once a force had been applied, because of deformation of the bone and a change in the line of action of the force relative to the posterior elements by rotation of the vertebra.

The test values obtained from the spines of children were lower than the figures for adults, but are otherwise similar. The point of attachment most vulnerable to failure by any technique is the thoracic spine.

Charnley (1960, 64, 65) and Charnley and Kettlewell (1965) have used self-polymerizing acrylic to eliminate slip between a femoral head replacement prosthesis and the femur of humans. The polymer acts as a "grouting" increasing the surface area for the transmission of weight from the prosthesis to the femur.

In the animal experiments performed, the author was not able to substantiate the finding of bone necrosis reported by Wiltse, Hall and Steneshjem (1957). This may have been due to the relatively small amount of material used, or the fact that the posterior elements were cleared unilaterally with maintenance of blood supply to the transverse and spinous processes. No difference was found in the tissues adjacent to the cooled as compared with the uncooled polymer.

Reports on the toxicity of methyl methacrylate are conflicting. Henrichsen, Jansen and Krough-Poulsen (1952) recorded no reactions in 40 swine in whom the plastic was inserted, in a period of two to three months. Spealman, Main, Haag and Larson (1945) calculated an LD₅₀ of methyl methacrylate in dogs of 10 ml/kg. They found pathological changes in the lungs, liver and kidneys, the liver changes resembling those found in carbon tetrachloride poisoning. High concentrations of methacrylate produced ataxia and depression with paralysis of the respiratory center. In a series of skin tests, they found 20 % manifestation of sensitivity to the free monomer and no reaction to the polymerized material. Kiaer

(1951) performed a series of experiments on young pigs, and two to three months following implantation found neither radiological nor pathological evidence of reaction.

Nyquist (1958) stated that cold or self-curing acrylics contained approximately the same amount of free monomer as the heat cured, but Smith (1959) stated that the presence of unconverted monomer was particularly dependent upon the temperature of curing. He also noted the continuation of polymerization following the early peak. Initial rapid depletion of the surface residual monomer occurs in water solution, but with depletion of the surface layer, a slow defusion occurs from within.

The self-polymerization of acrylic initially result in approximately 5 % to 10 % of the free monomer being retained in this form. It seems apparent that the monomer is a toxic material, but it is doubtful whether the amount of free monomer available, as currently used or investigated in this series, would be dangerous to man. However, while the use of the plastic seems justifiable for the reasons listed by Charnley (1960, 1964, 1965) in an elderly patient, it is the author's belief that the use of this material in a child of scoliotic age was not justifiable. With the development and testing of further plastics, however, it is probable that one will be found that will be safe for implantation. For the present time, it would seem best to await such development and use the relatively inert surgical alloys.

The failure values obtained by static testing of children's spines are frequently lower than those measured by the force-measuring distractor tool designed by Armstrong and Connock (1965), for use in the instrumentation procedure of Harrington. Harrington, himself, has advised restraint in the application of force when using his technique (1964).

The following questions are, therefore, raised:

- 1) What force is needed to correct a scoliotic deformity?
- 2) What posterior structures resist correction?
- 3) Is a force applied at the time of insertion maintained, or does it deteriorate with time?
- 4) What effects do recovery from anesthesia, sitting, and standing have on the force applied to the spine by a correctional instrument?

It was concluded that these questions should be answered if the technique of instrumentation was to be improved, and, the answers could only be provided by intravital measurements.

IV Intravital measurements

After exploring various possible methods of obtaining intravital measurements, both at the time of surgery, and in the immediate postoperative period, it was concluded that the most accurate technique would be the employment of strain gages attached to the actual equipment employed in a spinal instrumentation procedure. Strain gages of various types are available, but the electrical gages are the most easily adaptable to the required conditions imposed by surgery.

Electric strain gages depend upon the property that the resistance of a metal wire changes when the wire is elongated. The relation between the relative change in resistance and strain is called the "gage factor". In order to measure strain, the resistance must not only be bonded to the material in which the strain is to be measured, but must be connected to an apparatus capable of measuring small changes in resistance. The most suitable electrical circuit for this type of measurement is the Wheatstone Bridge,

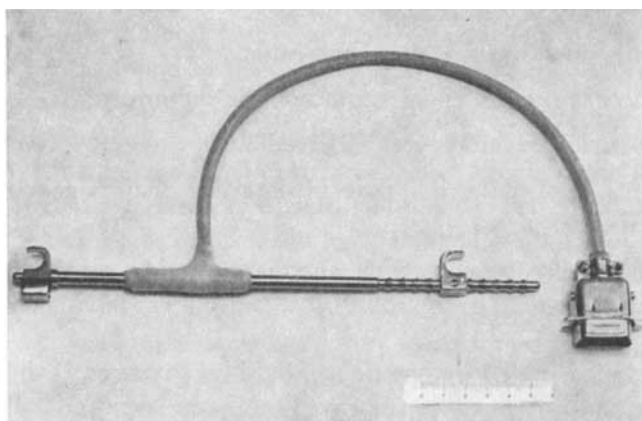


Fig. 19. *Distraction rod with strain gages in place isolated by Silastic 382.*

various modifications of which principle are used for direct measurement of strain. Such modifications were utilized in these intravital measurements.

The use of electrical strain gages presents two major problems when inserted in the body. The first of these is the isolation of the gage from moisture. The material selected in these experiments to achieve such isolation was Dow Corning Medical Silastic 382 and 385 Elastomer. The other problem involves the selection of a bonding material that is not only suitable for the gages employed but will accept the temperatures required to achieve sterilization of the apparatus. The bonding materials finally used were Budd GA-5 and GA-60. These cements were found to be satisfactory for use with Budd C9-111 and C9-114 strain gages.

FORCE COMPONENTS

In order to analyse the force components along the x, y and z axes, an arrangement of 10 gages was utilized (see Fig. 21). With this configuration, it was possible to measure the axial and transverse loads. By placing the gages in electrical series, the strain dependent on the moment of axial eccentricity was eliminated. Gages A-B measure compressive load and C-F and G-J measured the moments from the axial and transverse loads, from which the transverse loads can be evaluated.

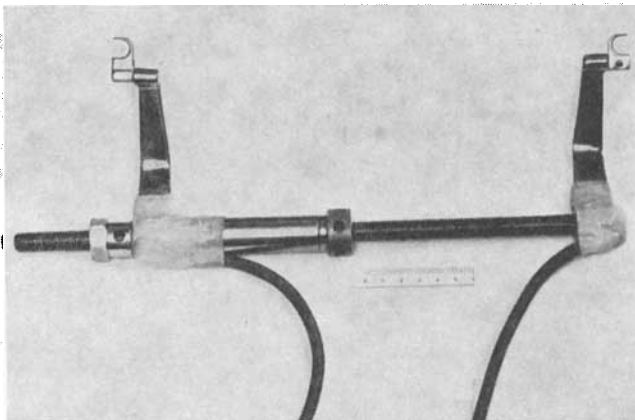
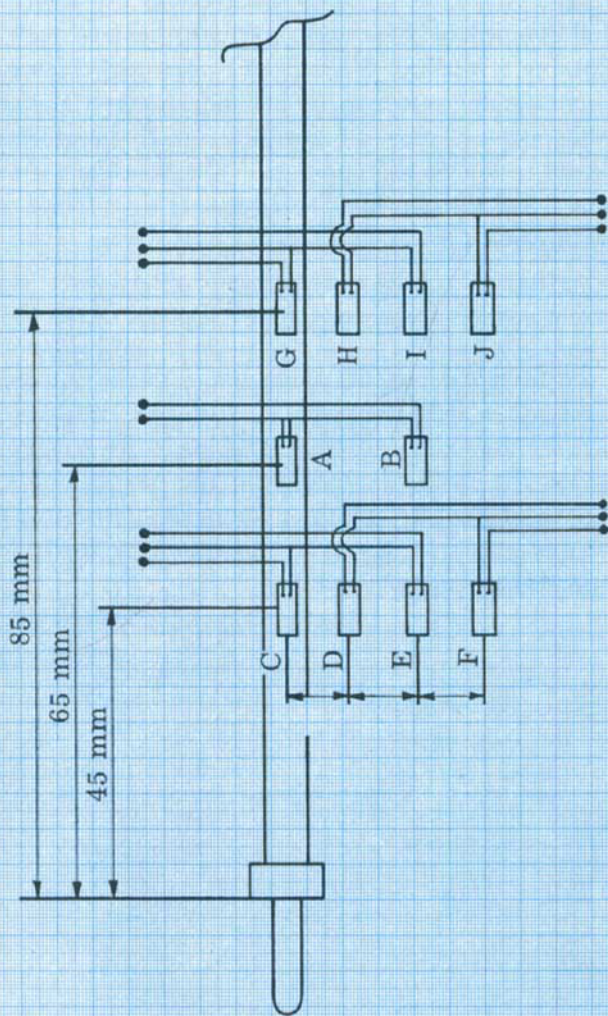


Fig. 20. *Distraction outrigger with gages applied.*



Mounting arrangement of strain gages on Harrington rod

Fig. 21. Illustrating placement of strain gages on distraction rod.

The total stress, σ_t , at every point in the rod, consists of three parts σ_c , $\sigma_{b1} + \sigma_{b2}$, where σ_c is that stress due to compression from the axial load and σ_{b1} is the stress due to bending from the eccentricity of the axial load and σ_{b2} is the bending stress derived from the transverse load.

To calculate these stresses, use is made of Hooke's Law

$$\sigma = E \cdot \epsilon \quad (1)$$

(where E is the modulus of elasticity and ϵ the recorded strain).

$$\sigma_c = \frac{P}{\pi r^2} \quad (2)$$

$$\sigma_{b1} = \frac{P \cdot a}{\frac{\pi r^3}{4}} \quad (3)$$

(where P is the axial load, a the eccentricity, and r the radius of the rod.)

From equation 2

$$\begin{aligned} P &= \sigma_c \cdot \pi r^2 \\ &= \epsilon_c \cdot E \pi r^2 \end{aligned} \quad (4)$$

and ϵ_c is obtained from gages A-B.

In order to measure the forces prior to the exposure of the posterior elements over the apical section of the curve, an instrument was designed similar to the outrigger of Harrington (Zimmer No. 1248). Only the axial component being desired, two strain gages were mounted to each arm of the outrigger and the load computed (Perey and Lissner, 1962).

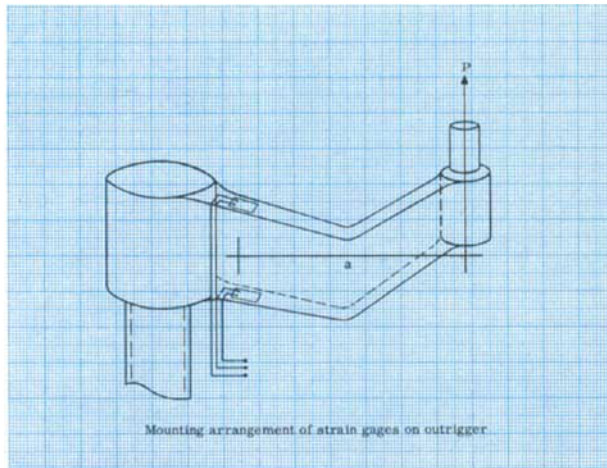


Fig. 22. Illustrating placement of strain gages on outrigger distraction device.

The distraction force P produces the desired moment Pa , a being the distance of the line of action of P from the center of the strain gages (see Fig. 22).

In this theoretical consideration, the additional bending moment due to the hook is small and is ignored.

$$\sigma = \frac{Pa}{\frac{th^2}{6}} \quad (5)$$

(where t is the thickness and h the height of the cantilever arm.)

Substituting Hooke's law, equation 1

$$P = \frac{E\epsilon th^2}{6a} \quad (6)$$

Measurements were made on a Bofors Balancing and Calibrating Unit Type BK-3 with 5 Channels and a Peekel 12 Channel Electronic Strain gage measuring bridge Type 112DA. Recording was done by a Honeywell 906T Visicorder with a M100-120A Heiland Miniature Galvanometer and an ABEM Ultralette 5650 with Type 5831/N Galvanometer.

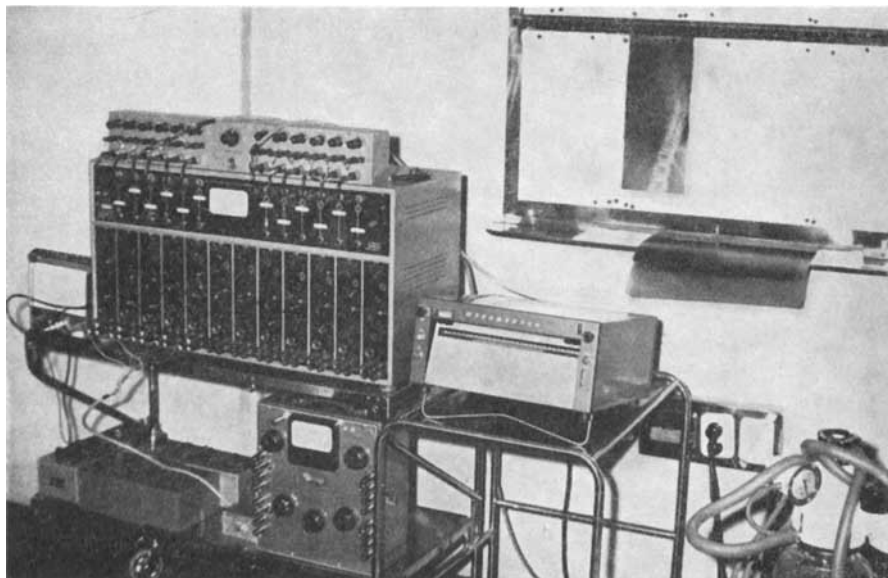


Fig. 23. Electronic equipment for measuring strain (Peekel bridge, type 112DA and ABEM Ultralette 5650).

CALIBRATION

Calibration of the distractor gages was carried out with hooks in place, at various possible angles of the hooks relative to the instrument. Because of the arrangement of strain gages on the rod, however, it was not essential

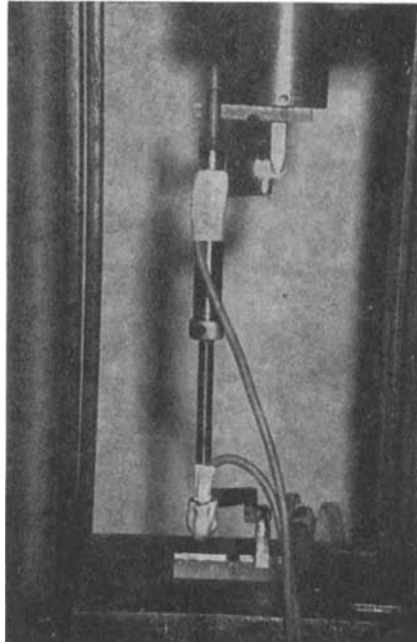


Fig. 24. Calibration of distraction outrigger in materials testing machine.

that a definite position be established and maintained with recording of the force components. A calibration curve was plotted for each device prior to insertion in the patients. This was done in a materials testing machine with an inaccuracy of less than 1 %. The calibration was further verified by applying weights to the hooks with the devices fixed in a rigid support. Postoperative recalibration of the outrigger device indicated maintenance of accuracy.

STERILIZATION

In order to avoid excessive moisture and excessive temperature, a Waldén autoclave was utilized. In this autoclave, the humidity does not exceed 1 %, and the sterilizing temperature does not exceed 115 degrees C. The sterilization time was 15 minutes, and routine cultures of the instruments, prior to insertion, revealed the absence of bacterial flora. (Rydell, 1966)

SELECTION OF PATIENTS

Three patients selected for intravital measurements were candidates for surgical treatment of their scoliosis by the criteria previously outlined.

The first patient was a 15-year old girl who continued to show progression of her scoliotic deformity, despite treatment by a Milwaukee brace. Immediately prior to the surgical procedure, her erect film by the Ferguson technique measured 48 degrees and the recumbent 38 degrees (Cobb 54 and 41 degrees), and it was noted that her iliac apophyses had not completed their excursion.

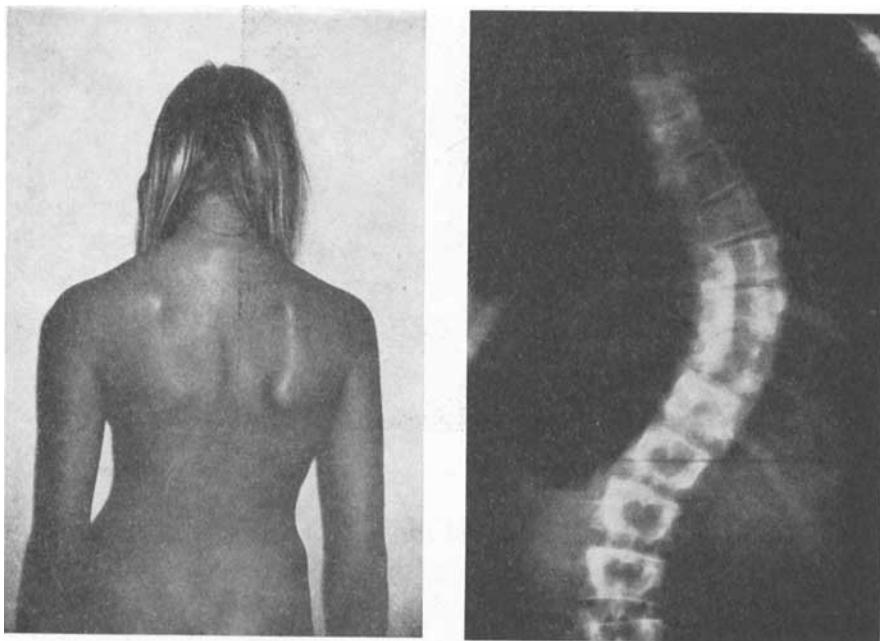


Fig. 25 a, b. *Photograph and erect roentgenogram of Patient 1.*

The second patient was a 14-year old girl whose erect curve measured 40 degrees by the Ferguson technique and 32 degrees in the recumbent view (Cobb 51 and 49 degrees). She evidenced some immaturity and the excursion of the iliac apophyses had just commenced. She, too, showed evidence of progression, particularly in the four months prior to surgery. The third patient was a 15-year old boy with a very severe inflexible idiopathic scoliosis. Measurement of his erect film indicated a 59 degree



Fig. 26 a, b. *Photograph and erect roentgenogram of Patient 2.*

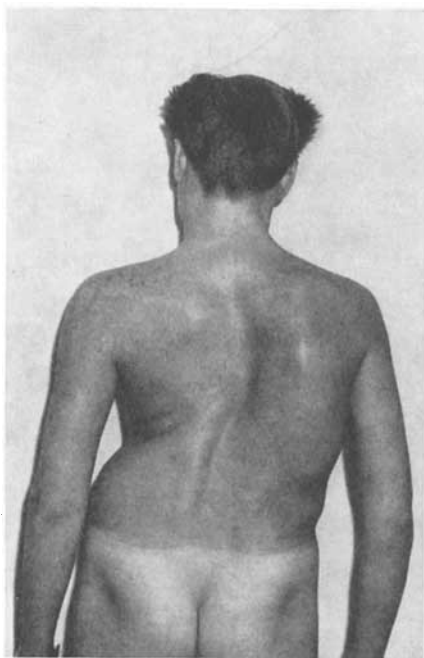


Fig. 27 a, b. *Photograph and erect roentgenogram of Patient 3.*

curvature which corrected only 5 degrees in the recumbent view (Cobb 88 and 84 degrees). This boy had manifest increased deformity in the four months prior to surgery, and by his age, sex and the appearance of his apophyses, was considered to have sufficient further growth to warrant surgical correction.

Prior to surgery, cardiopulmonary studies were carried out. A reduction in vital capacity was evidenced in all patients. On the basis of the clinical and electromyographic studies, there was no possibility of classifying these three curves otherwise than as right dorsal idiopathic scoliosis.

	Erect°	Recumbent°	Extent of Curve	Vital Capacity
Patient 1	48(54)	38(41)	T6-L1	2.55/3.75
Patient 2	40(51)	32(49)	T4-T11	3.30/4.19
Patient 3	59(88)	54(84)	T5-T12	2.44/3.80

RESULTS

In the three operative procedures during which recordings were taken, every attempt was made to adhere to the established technique of spine instrumentation. The safety of the patients was in no way jeopardized as a result of the study carried out.



Fig. 28. Roentgenogram of distraction rod (Zimmer No. 1250) with strain gages applied in situ. (Patient 1).

Patient 1 (see Fig. 25 a, b)

In the first patient, a Harrington distraction rod with attached strain gages was inserted. Continuous recordings were made during the operative procedure in the course of which the patient's curve was corrected to 20 degrees (Cobb 19 degrees). A maximal force of 18 kp was developed during the elongation of the distraction rod to the final notch. It was not believed desirable to proceed further, as considerable resistance was encountered at this level.

An episode of coughing on recovery from anesthesia is shown in diagrammatic representation of the recorded forces.

During the following hours, periodic recordings were made which indicated a base line of about 14 kp. At one such recording, during the seventh hour, the patient vomited, with the strain gages indicating forces up to 69 kp. At 24 hours following insertion, the patient was allowed to sit on the side of her bed and stand. Forces up to 20 kp were recorded, about 4 kp above the base line.

AXIAL FORCE (KILO-PONDS) CALCULATED DURING OPERATION ON PATIENT 1

1st notch of rod	4 kp $\pm$ 2
2nd " " "	8 kp $\pm$ 1
3rd " " "	18 kp (max)
Equalized at (5')	10 kp $\pm$ 1
Hand pressure on thorax	10 kp $\pm$ 2
Recovery from anesthesia	10 kp $\pm$ 1
Coughing	37 kp (max)
Vomiting	69 kp (max)
Prior to sitting	14 kp $\pm$ 1
Sitting	18 kp $\pm$ 2
Standing	18 kp $\pm$ 2

Following these recordings, the electric leads were removed, and spine fusion was performed with autogenous bone at a second stage.

PATIENT ONE

- 1 Distraction
- 2 Distraction
- 3 Distraction
- 4 Hand pressure
- 5 Anaesthesia recovery
- 6 Coughing
- 7 Vomiting
- 8 Sitting
- 9 Standing

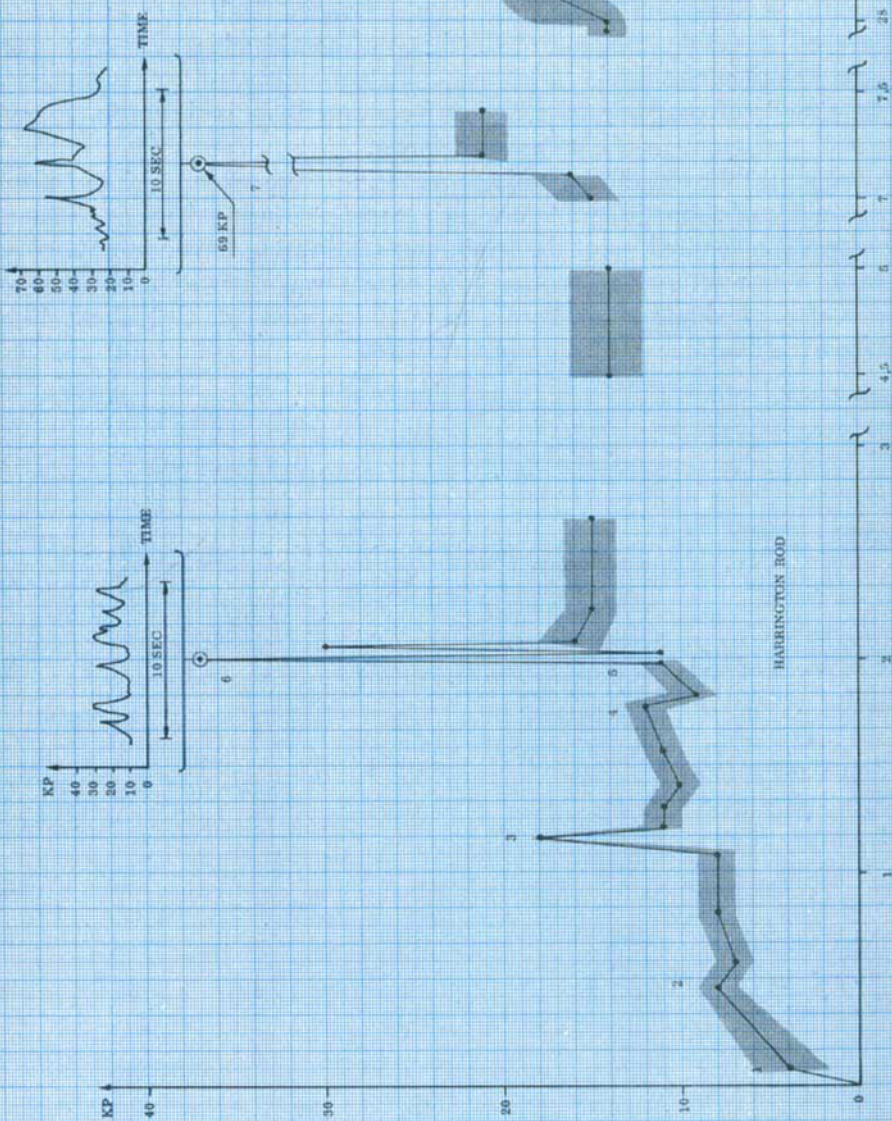


Fig. 29. Axial force measurements, Patient 1.

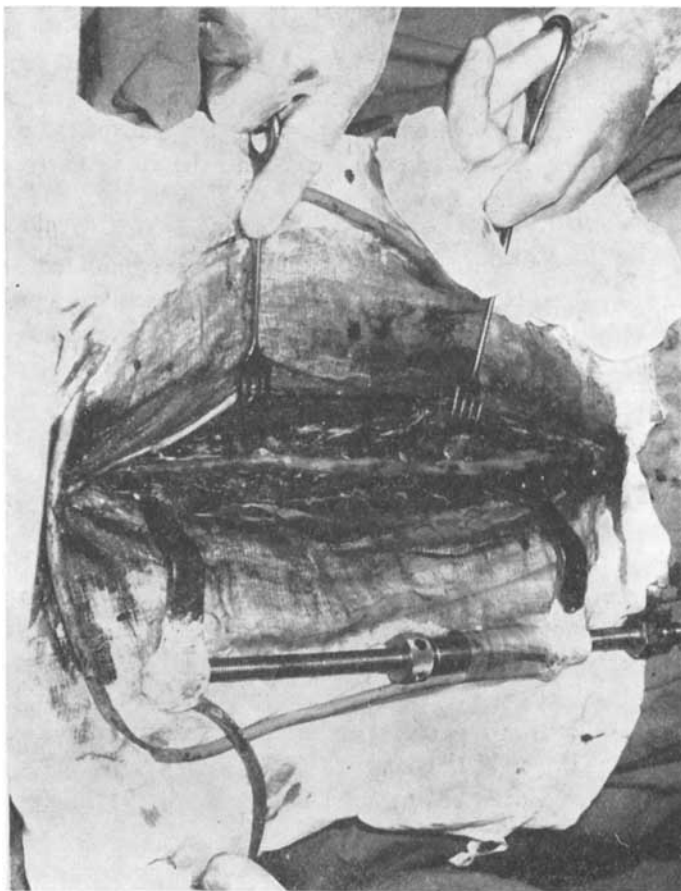
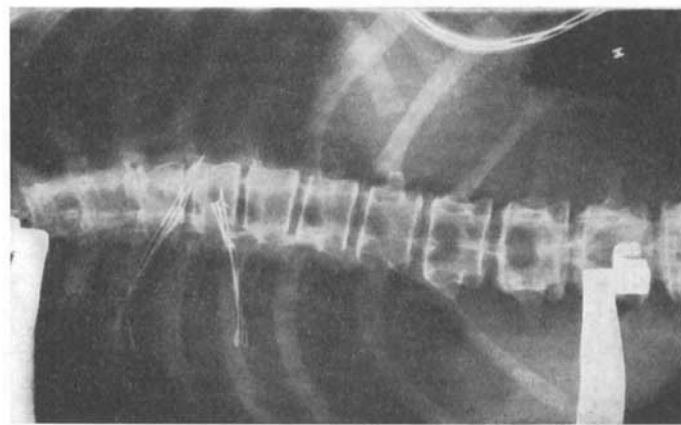


Fig. 30 a, b. Distraction outrigger device during recording and roentgenogram showing correction. (Patient 2).

Patient 2 (see Fig. 26 a, b)

In order to assess the role of the paraspinous musculature and ligaments in resisting correction, small midline incisions were used to expose the intended sites for insertion of distraction hooks at the ends of the primary curve. An outrigger device was then inserted and the curve corrected by a distraction force to 28 kp.

The concave and convex musculature was electrically stimulated and the resulting range of values are indicated. Release of the musculature produced little alteration in the level of forces recorded and cutting the intertransverse and costotransverse ligaments caused a decrease in axial force of 1 kp.

AXIAL FORCE (KILO-PONDS) CALCULATED DURING OPERATION ON PATIENT 2

After outrigger correction to 10 degrees	28 kp $\pm$ 0.5
Electrical stimulation of concave erector spinae M.	22 kp $\pm$ 1
Electrical stimulation of convex erector spinae M.	22 kp $\pm$ 1
Following release of concave superficial and deep musculature	21 kp $\pm$ 0.5
Following release of convex superficial and deep musculature	22 kp $\pm$ 0.5
Following section of CT & IT ligaments	21 kp $\pm$ 0.5
Prior to attachment of convex compression system	31 kp $\pm$ 0.5
Maximal compression (prior to failure)	30 kp $\pm$ 0.5
At injection of celocurin (50 mg)	20 kp $\pm$ 0.8
Complete paralysis	12 kp
Lifting to bed from operating table	25 kp $\pm$ 1
Completely recovered from anesthesia	19 kp $\pm$ 0.5

By elongating the concave outrigger, the distraction force was increased to 31 kp, and the Harrington compression system applied using 6 hooks. Maximal tightening of the system to the point of multiple simultaneous transverse process fracture is shown.

A recording distraction rod was inserted and the compression system removed. Correction to 10 degrees (Cobb 20 degrees) was obtained. A base line was established with the patient able to breath spontaneously, following which, a paralyzing dose of celocurin was administered (50 mg), causing a significant fall in axial load at complete paralysis. Following transportation to the Recovery Room, the leads were removed.



Fig. 31. *Compression system application and recording from outrigger. (Patient 2).*

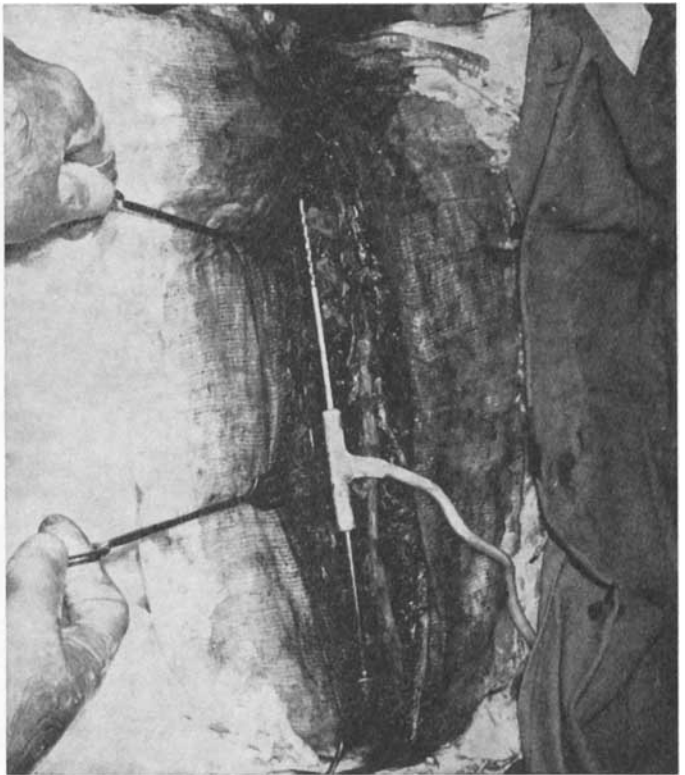
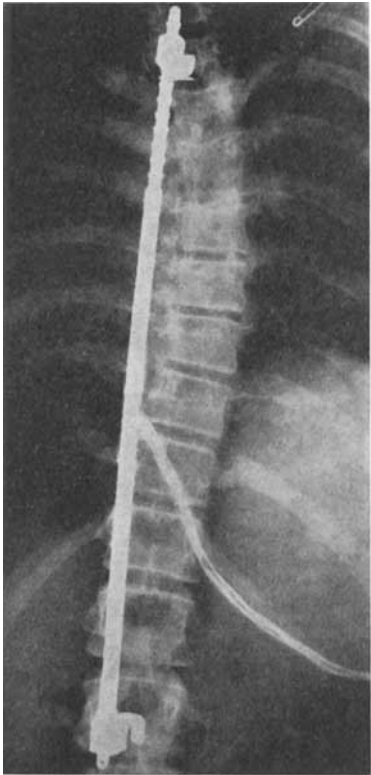


Fig. 32 a, b. *Distraction rod in place prior to closure. (Patient 2).*

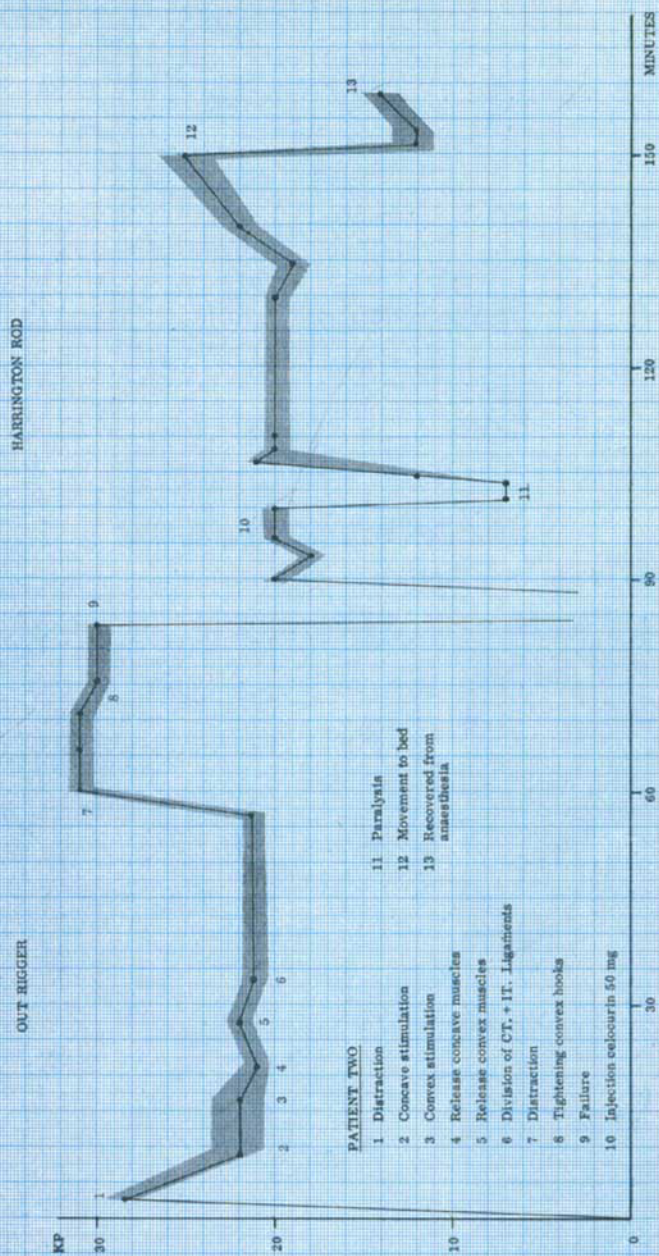


Fig. 33. Axial force measurements, Patient 2.

PATIENT THREE

- 1 Distraction
- 2 Distraction
- 3 Distraction
- 4 Concave muscle release
- 5 Release interspinous ligaments
- 6 Start releasing transverse ligaments
- 7 Finish releasing transverse ligaments
- 8 Convex muscle release
- 9 Distraction
- 10 Failure

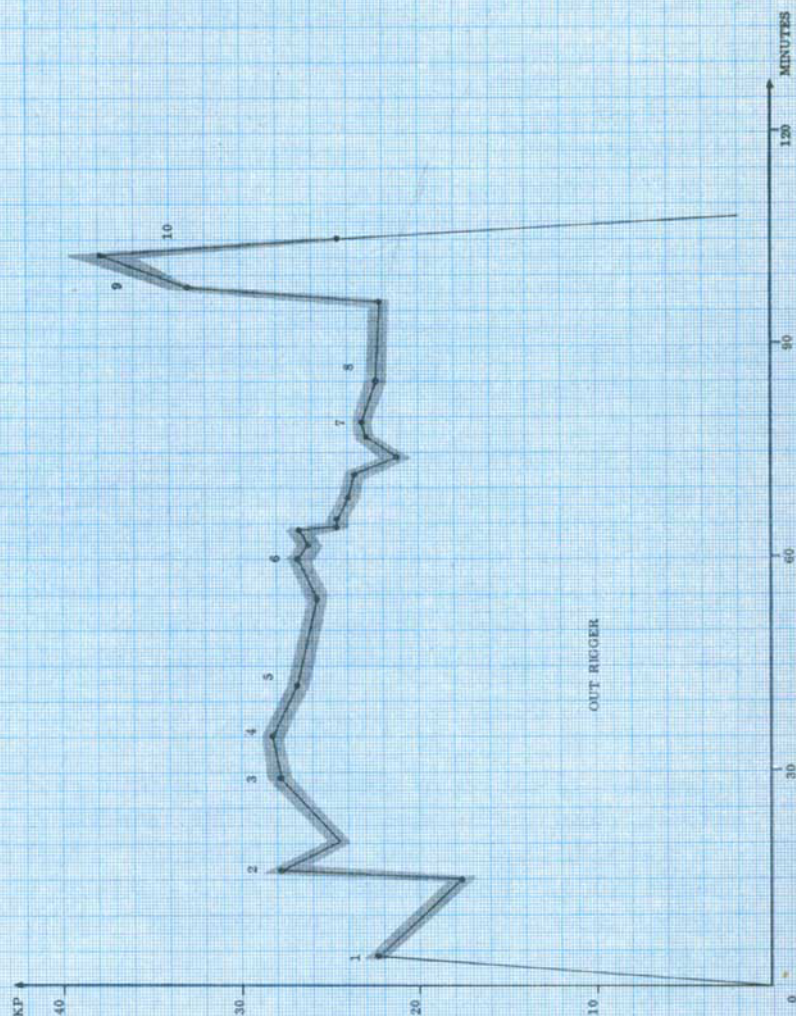


Fig. 34. Axial force measurements, Patient 3.

Patient 3 (see Fig. 27 a, b)

After insertion of the monitored outrigger device as outlined above, the axial load in this patient was slowly increased to 28 kp. The concave musculature was released and the intertransverse and costotransverse ligaments cut one level at a time. Releasing the apical transverse processes produced a fall of about 1 kp per level.

AXIAL FORCE (KILO-PONDS) CALCULATED DURING
OPERATION ON PATIENT 3

Following distraction	22 kp $\pm$ 1
After 10 minutes	17 kp $\pm$ 1
Further distraction	28 kp $\pm$ 1
After 5 minutes	25 kp $\pm$ 1
Prior to release of concave musculature	28 kp $\pm$ 1
Following release of superficial & deep concave musculature	28 kp $\pm$ 1
Following section of interspinous ligaments	27 kp $\pm$ 1
Following section of CT & IT ligaments	23 kp $\pm$ 1
Following release of convex superficial & deep musculature	22 kp $\pm$ 1
Increased distraction to failure	38 kp $\pm$ 2

Release of the convex musculature is shown. In an attempt to attain more correction, force was increased to 38 kp. The motion incident to positioning for a PA roentgenographic examination was sufficient to cause the upper hook to "cut out" with immediate fall in force to zero. The hook was replaced at the next higher level and a conventional distraction rod inserted. Correction to 44 degrees (58 degrees Cobb) was achieved in this patient prior to spine fusion with supplemental autogenous bone.

DISCUSSION

Examination of the results obtained from the three patients on whom intravital measurements were made, indicate considerably lower forces than was anticipated. In view of the failure of the hook in patient 3 (Zimmer No. 1253) with a load of 38 kp, it is believed that the forces measured under static extravital conditions are probably higher than can be tolerated in the body.

The final axial force on the hooks as applied by the distractor tool was 20—30 kp. This provided the feel of resistance mentioned by Harrington (1964).

A considerable degree of tissue relaxation was demonstrated during the

initial stages of correction. A deterioration of 4 kp was noted in 10 minutes, following which the force fell more slowly.

Subperiosteal dissection of the paraspinous musculature, and presumably denervation (under anesthesia), did not alter the axial load to any significant degree. However, particularly in the third patient, selectively cutting the intertransverse and costotransverse ligaments at the apex and immediately adjacent thereto, caused a perceptible reduction of force. This was only true of those ligaments at the apex. No change was determined by ligamentous section at the ends of the primary curve, nor was any change recorded by cutting the interspinous ligaments.

Although under deep surgical anesthesia, the recorded force was significantly reduced (40 %) by complete paralysis. The return of spontaneous respiration was associated with the return of the axial load to the level present prior to the administration of the drug.

The Harrington compression rod, using 6 hooks, was found to reduce the axial load on the distraction system by about 1 kp. That the amount of correctional force employed was maximal was indicated by multiple simultaneous fractures of the transverse processes.

Recovery from anesthesia, with the return of voluntary muscular control, did not alter the recorded force. However, coughing and particularly vomiting, were associated with large brief increase in the force on the hooks.

The action of sitting and standing were accompanied by considerable fluctuation in the recorded force, but the stabilized level was only 4 kp above the base line.

V Summary and conclusions

A review of the extensive literature on the etiology of scoliosis reveals a singular lack of facts on which it has been possible to develop sound hypotheses. Many authors have advanced theories, some of which have been partially substantiated by animal experimentation, which have been used to formulate new and presumably improved methods of treatment. That these procedures have not stood the test of time has been evidenced by the still newer methods that have replaced them. Such has been the rule, but a few exceptions do exist.

The Hibbs spine fusion, the Risser turn-buckle jacket, the Milwaukee brace, and very few others have established a definite place in treatment. Within the last few years, because of the work of Harrington and others, increased attention has been directed toward improved correction of the deformity in established scoliosis. There are many who would logically question the desirability of striving for a straight spine, or at least one that appears to be so, on the grounds that such attempts might endanger the vital contents of the trunk. Certainly, catastrophes have occurred that make mandatory a cautious approach, that places the safety of the patient first and foremost. However, within these limits, it is believed that progress can be made and new attempts should be encouraged to improve existing forms of treatment.

At the present time, little is known about the etiology of idiopathic scoliosis. Encouraging work is being done by Ponseti on the possible metabolic significance of the disease, and by James on the inheritance. Until such time as the pathogenesis is established and can be controlled, treatment will continue to depend on mechanical correction and maintenance.

As the external application of force to the thorax to correct spinal deformity is mechanically inefficient, several surgeons have sought ways of increasing this efficiency by applying force directly to the spine. The limiting factor, however, has frequently been the strength of the attachment, particularly in the thoracic area, where many surgeons performing

spinal instrumentation have had the unpleasant experience of having their carefully placed hook cut through the interarticularis. Such are the problems with instrumentation that some authors, in reviewing their patients, have not found their results to be improved over those obtained with conventional plaster jacket treatment.

With these problems in mind, it was believed necessary to investigate the strength of conventional methods of attachment to the spine and explore other systems that might be less liable to failure. In doing so, a technique which used a mold of the posterior elements of methyl methacrylate was developed which proved to be significantly stronger than existing techniques, as tested statically on autopsy specimens. However, the toxic properties of the material are due to free monomer which is present in about 10 % concentration with temperature controlled autopolymerization (40 degrees C. $\pm$ 2 degrees).

Although the amount of monomer we have used is small, it was concluded that the implantation of acrylic in a child was unjustifiable. In all probability, less toxic plastic materials will be developed in the future which would permit the safe use of such a technique.

The limiting factor on the strength of any attachment being the area of contact, a stainless steel hook was designed that closely approximated the anatomy of the interarticularis and inferior thoracic facet. Although having only 9 % greater surface area than the largest commercially available hook, the tested strength was significantly greater. It was presumed that a reduction in stress concentration due to the contour, caused the difference in levels of failure.

The Gruca hook, as tested, was found to fail at about $55 \text{ kp} \pm 10$. This failure occurred before the pedicle, to which it would be attached in an *anterior allopasty* procedure. Because of the increase in angle, or spread, with failure of these hooks, it was believed that this would create considerable danger to the cord. Such failure could be corrected by a stronger design if it were desired to exert forces in excess of 45 kp.

The application to patients of information obtained from testing specimens extravitally, can only be made with considerable reservation. Unfortunately, no accurate measurements had been carried out of the actual force necessary to correct a scoliotic spine, nor was any information available on the rôle of various elements in either causing deformity or resisting correction.

To accomplish these measurements, electrical strain gages were employed on an outrigger device and Zimmer No. 1250 rods to act as force transducers.

Three patients were selected for intravital measurements who required

correction and fusion by usual surgical criteria. The first two patients had flexible curves, the third a resistant inflexible curve of severe degree. Measurements taken during spinal instrumentation indicated that flexible curves may be readily corrected (60 % and 75 %) by forces of 20—30 kp, whereas inflexible curves may be corrected only 25 % by forces of this magnitude. A force of 38 kp was sufficient to cause failure of the thoracic attachment, necessitating reposition of the hook at a higher level. Various releases were carried out of the posterior structures to determine whether these resisted correction. In general, there was little change recorded by releasing the paraspinal musculature or interspinous ligaments. In the third patient, section of the apical intertransverse and costotransverse ligaments produced some perceptible drop in force, but when this was performed on the second patient, the results were inconclusive.

Complete paralysis caused a significant fall in force when compared with that present during surgical anesthesia. Coincident with the return of spontaneous respiration, the axial force returned to the original level.

On regaining voluntary muscle control, there was no significant change in force recorded. Coughing, and particularly vomiting, were associated with momentary high forces. These were considerably higher than those obtained on voluntary sitting and standing.

Re-examining the spinal instrumentation procedure with the information obtained from these extravital and intravital measurements, it is apparent that the weak point of attachment of the distraction rod is to the thoracic spine.

In view of the deterioration curve of the axial force, distraction should be attained in slow increments giving the tissues adequate time to adjust. With present commercially available methods of attachment, the distraction force should not exceed 30 kp, although in view of the number of patients in whom recordings were made, such an absolute figure is not significant. The notches on the distraction rod (Zimmer No. 1250) are 6.3 mm apart. Under certain circumstances, one notch may cause a very considerable change in force levels, raising the question of the desirability of having these so widely spaced. This was noted in all three patients, but was particularly important in the first procedure, where the proximal notch was too little force and the distal too much.

As far as determined in this study, the compression system for the concave side of the curve, contributed insignificantly to reduction of the magnitude of the forces on the concave.

It is not believed possible to use the measurements obtained to either advance or negate any of the theories of the etiology of scoliosis. However,

one cannot but be impressed by the small size of axial force necessary to achieve acceptable correction of the two flexible curves.

Further, the marked drop in force which was associated with paralysis of the intercostals, raises the question of their possible rôle in idiopathic scoliosis.

In conclusion, it is believed that this study has provided a method for accurate measurement of the forces resisting correction in scoliosis, as well as suggesting related forces, which may contribute to the development of the deformity.

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