Bone Growth after Spine Fusion

A Clinical Survey

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About 1783, John Hunter placed lead shot two inches apart in the diaphysis of a young pig. When the pig was fully grown and was slaughtered, the shot were still two inches apart. This led him to believe that bones are not elongated by new matter being interposed in the interstices of the old.

For many years the mechanism of longitudinal growth of bone has been a controversial subject in the literature. As eminent an authority as Clopton Havers believed that all parts of the bone tissue of the skeleton took part in longitudinal growth, and that this so-called interstitial growth of bone was the normal form of skeletal growth. Kornew in 1929, Policard in 1930, and Hellstadius in 1947, have all defended some type of interstitial growth of bone.

The majority opinion, especially as roentgenography and microscopy have widened the study of the subject, has been that all growth in length of the diaphyses of long bones takes place at the epiphyseal cartilages, whereas growth of bone in other dimensions occurs through hyaline-cartilage proliferation—as in the epiphyses—or through fibrous-tissue proliferation—as in the periosteum and flat bones. After a careful survey of all arguments for and against this theory, Lacroix concluded that: "The structure of arguments denying the intervention of any interstitial bone growth remains intact".

However, just as the argument seemed settled, new observations arose to confuse the picture. Various investigators reported the apparent lengthening of fused segments after spine fusion in children and in young experimental animals. If this were true in the solidly fused spine, it would mean one of two things: either the fusion area broke down at one time or another or there was interstitial growth of bone in the fusion plate.

On the experimental plane, Bisgard and Musselman performed lateral inter-body fusion on the spines of young goats and reported that in every instance fusion by a firm bone bridge resulted. As growth of the spine continued, they noted that this bone bridge became elongated to accommodate itself to the longitudinal growth of the vertebrae. They concluded that under certain circumstances, transplanted bone is capable of intrinsic growth in length.

On the other hand, in the same year, Haas, after performing spine fusions in puppies, noted that just as soon as the fusion was firm in the spinous processes, there was no yielding in the fused spine to the growing forces of the bodies. However, Haas found definite lengthening of the grafted area in almost all of his experiments, but he had no serial roentgenograms, explorations, or other ways to determine when the "fusion was firm". Therefore, the most he could logically infer was that at the time of sacrifice, when the animal was almost fully grown, there was generally solid fusion and that growth had been somewhat suppressed at some time. He noted that when the markers were attached to the graft, there was no separation of the markers. However, this important observation was based on two dogs only.

Odelberg-Johnson[14] performed spine fusions on rabbits, but noted gross pseudarthroses at almost every interspace. He concluded that the growth in length of the spine in these animals took place at these defects. However, these were clinically obvious defects, often with a true joint cavity completely lined with cartilage, and gross motion was often demonstrable in bending roentgenograms. Hence, the findings in these animals are scarcely comparable with those in children with apparently solid spine fusions. In general, therefore, spine-fusion experiments fail to throw much light on the problem because of the difficulty in getting proved solid fusion in young animals.

Clinical reports are as confusing as experimental ones. Hallock, Francis, and Jones, and Risser indicated that growth of the fusion mass does occur. Risser noted that the fusion mass is elongated with growth of the vertebral body and

1. By our method the centers of the vertebral bodies and mid-points of the pedicles were used as points of reference for all measurements. The two end vertebrae of the fused area were never included in any measurement. Thus, if the fusion extended from the tenth thoracic to the third lumbar vertebra, the distance between the center of the eleventh thoracic vertebra and the center of the second lumbar vertebra would be measured. Similarly, if the fusion extended one segment farther down to the fourth lumbar vertebra, the distance between the center of the body of the eleventh thoracic and that of the third lumbar vertebra would be used as reference points of measurement.

If pseudarthrosis was found between the tenth and eleventh thoracic vertebrae, an alternate measurement would be used. Since the restitution of the diseased area in the upper portion of the body of the first lumbar body is probably equivalent to the encroachment of the inferior surface of the third lumbar vertebra into the adjacent intervertebral disc, the distance between the central point of the body of the first lumbar to the central point of the body of the third lumbar vertebra could be used as an alternate measurement.

Finally, if the fusion extended down one more segment to the fifth lumbar vertebra, measurements could be made in the same fashion from the center of the eleventh or twelfth thoracic or from the center of the first or second lumbar body down to the center of the body of the fourth lumbar vertebra.

Whenever possible, diseased vertebrae were not used as points of reference for measurement.

Measurement of the control area under the conditions described here is illustrated. The points of reference are the centers of the bodies of the seventh and ninth thoracic vertebrae. Note that four vertebral plates are included in the control area being measured.

2. By the method of Hallock, Francis, and Jones, if the fusion area extended from the tenth thoracic to the third lumbar vertebra, the points of reference for the measurement of the length of the whole fusion would be vertebral plate *1* and vertebral plate *10*. Measurements of the normal vertebral bodies included within the fusion would be made from vertebral plate *1* to vertebral plate *4* and from vertebral plate *7* to vertebral plate *10*. Measurements of the normal posterior elements, the pedicles, would be made in a similar fashion between points *A* and *B* and between points *C* and *D* on the pedicles.

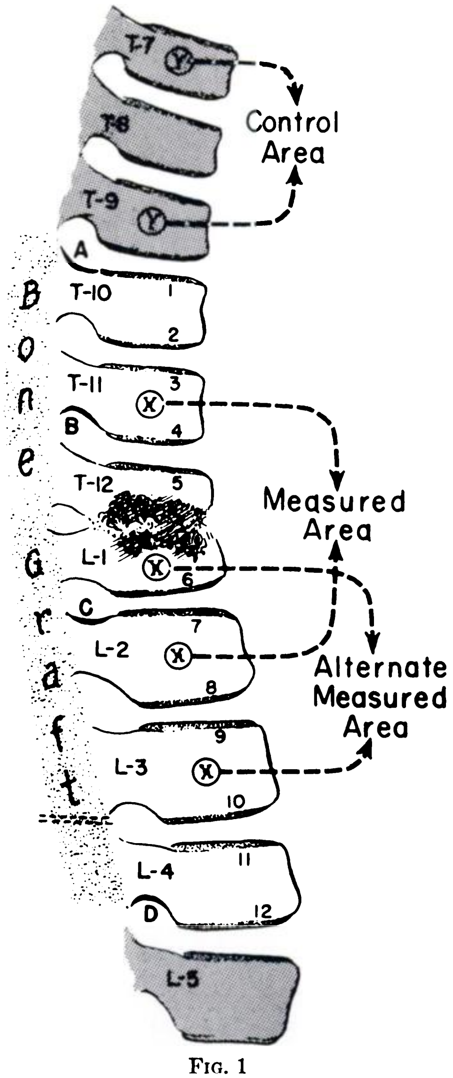

FIG. 1

Two methods of measurement.

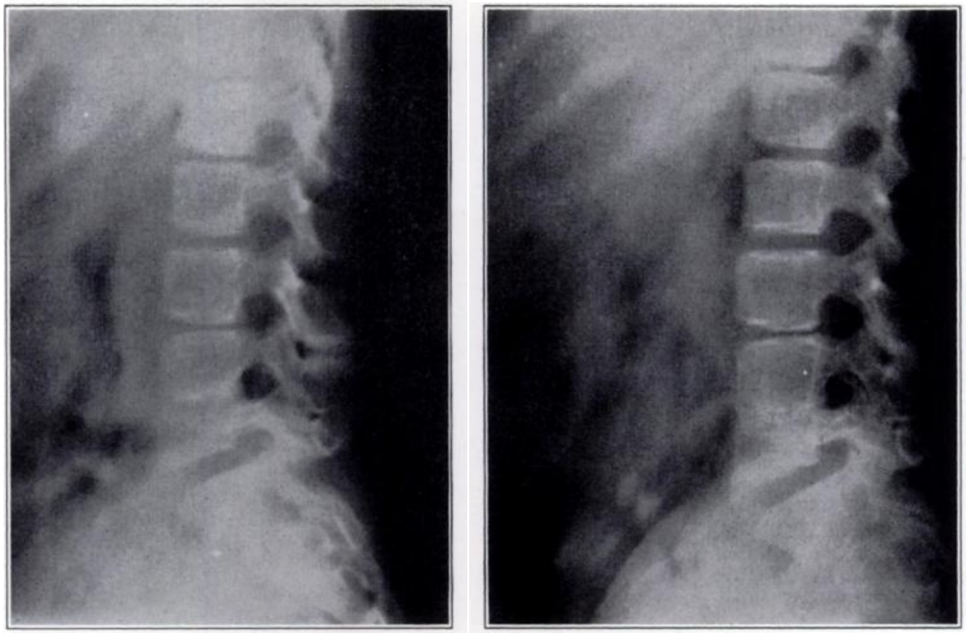

FIG. 2-A FIG. 2-B

Roentgenograms of Case G. C., on whom an Albee fusion was performed, extending from the third to the fifth lumbar vertebra. Pseudarthrosis between the third and fourth lumbar vertebrae appeared six months after operation and was still visible on a roentgenogram made on May 4, 1951, four years after operation (Fig. 2-A). Despite no treatment of any kind, this pseudarthrosis was bridged by bone, May 9, 1952, five years after operation (Fig. 2-B).

concluded that this was possible because of the biological plasticity of bone. Hallock and associates carefully measured the roentgenograms of fifteen Hibbs fusions that were performed in young children who were followed into adult life. These authors found in all patients continued growth of both the anterior and the posterior elements of the fused vertebrae.

Cleveland and associates presented a long-term follow-up study of spine fusions for tuberculosis in children and stated that: "Growth of the fused area was noted, the average growth being one and one-half inches and the least growth being three-quarters of an inch".

Completely opposed to these authors are the findings of Odelberg-Johnson [13], who also made a long-term follow-up of Albee grafts in human beings. He stated categorically that he had not observed increase in length of the whole paraspinal bone bridge in man. Ponseti and Friedman, in discussing changes in the scoliotic spine after fusion, wrote: "The growth of the fused segment, then, was nil or minimal except in the cases in which pseudarthrosis developed".

Another confusing question, raised but not explained in recent literature, is the bending of apparently solidly fused portions of the spine. After spine fusion for scoliosis, von Lackum and Miller observed that bending or giving way of the fusion will occur if the primary curve is overcorrected to the extent that balance of the trunk cannot be restored by straightening of the compensatory curves. Under these circumstances a gradual but sustained loss of correction occurs; occasionally through a localized area of deficient fusion, but often throughout the extent of the immature fusion mass in the absence of any pseudarthrosis, as proved by repeated negative surgical explorations.

Ponseti and Friedman also noted that correction in scoliosis was often lost and that the grafts bent, even when apparently solid. Hallock and Jones, in an earlier paper on tuberculosis of the spine, noted that: "Forward bending with resultant increasing deformity does not produce a pseudarthrosis in every instance. In many instances it results only in a bending of a somewhat malleable fusion plate. The sites of fusion in thirteen patients were explored for suspected pseudarthrosis, because of increasing deformity, and in each a solid fusion was found".

None of these authors attempted to explain how the bone bends or grows in length, merely stating that bone is "malleable", "plastic", or "ductile". But bone is not malleable, plastic, or ductile; it is rigid, even young bone is rigid. It can alter shape by apposition and absorption; it can grow by cartilaginous or fibrous proliferation; but it cannot grow, stretch, or bend in the mid-portion of a long fusion plate, unless one assumes there is such a thing as interstitial growth, or admits that there is loss of continuity of the bone in certain areas.

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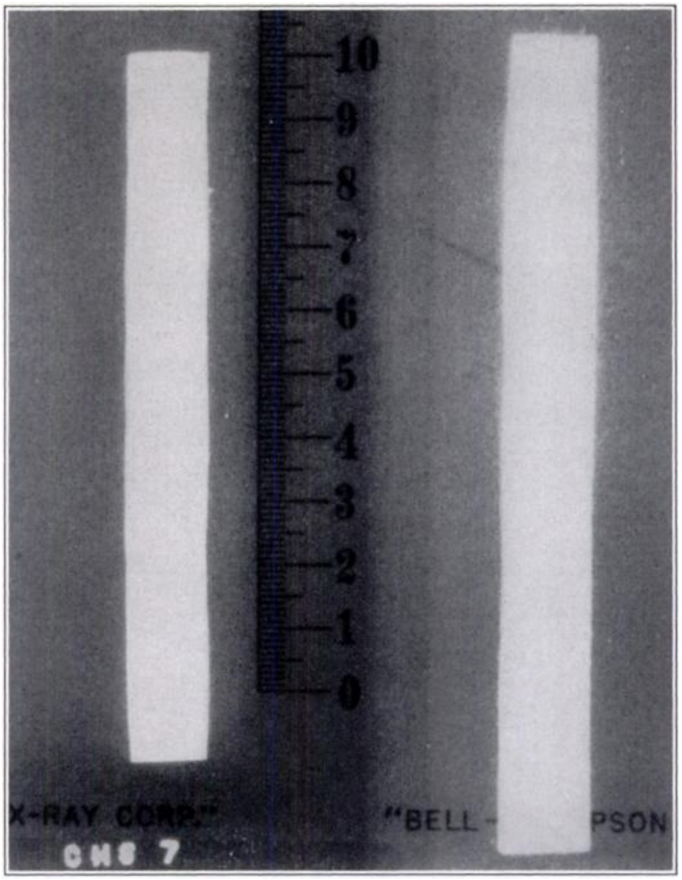

FIG. 3

Roentgenograms of two lead strips illustrating differences in magnification. The distance from the roentgen tube to the cassette was thirty-six inches (79.2 centimeters). Each lead strip was ten centimeters long and one centimeter wide. When this roentgenogram was made the strip on the left (at flat side of ruler) was held 8.5 centimeters above the film (the distance from the film to the spinous processes during a lateral roentgenogram of a six-year-old child, weighing fifty-five pounds) and the strip on the right was held 18.5 centimeters above the film (the distance from the film to the spinous processes during a lateral roentgenogram of an adult of average build weighing 150 pounds). The ruler was placed on the top of the cassette.

On this roentgenogram the strip on the left is 11.1 centimeters in length; the one on the right is 12.8 centimeters in length. Thus, the child's spine is magnified 11 per cent and the adult's spine, 28 per cent. This is a difference in magnification of the two strips amounting to 17 per cent. When the tube-to-target distance was increased to forty inches, as is sometimes the case when making roentgenograms of adult spines, the dimensions of the roentgenogram of the lead strip representing the adult changed very little. It is thus apparent that lateral roentgenograms of an adult's spine are magnified significantly more (17 per cent) in this instance than are those of a child.

FIG. 4-A

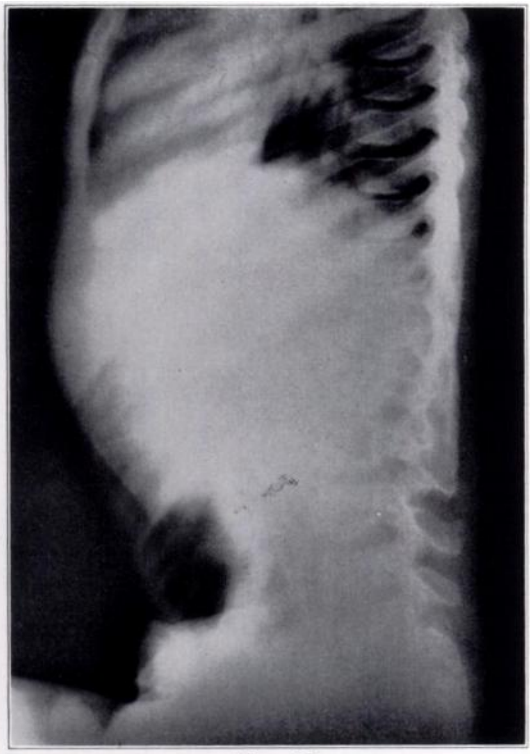

FIG. 4-B

Case S. S., tuberculosis of the spine involving the twelfth thoracic and first lumbar vertebrae. On June 20, 1951, a massive Hibbs fusion, using bank bone, was performed from the ninth thoracic to the third lumbar vertebra. Exploration of the graft with repair of pseudarthrosis between the eleventh and twelfth thoracic vertebrae was carried out on January 9, 1952. On May 21, 1952, the fusion was re-explored and found to be solid throughout its whole extent.

Roentgenograms of the spine were obtained at least once a year, from 1952 to 1958. The best were those made on December 16, 1952, when the patient was five years of age (Fig. 4-A), and on August 9, 1958, when the child was ten and a half (Fig. 4-B). Note that some straightening of the kyphosis had occurred during this interval of five and a half years.

Using these roentgenograms, we determined the increase in height of the fused and the unfused normal vertebrae, employing first our method and then that of Hallock, Francis, and Jones.

By our method the fused area (the six undamaged epiphyseal plates) between the tenth thoracic and second lumbar vertebrae increased as follows:

	12/16/52	7/9/58	Increase (per cent)
Distance between mid-bodies	6.9 cm.	7.5 cm.	9
Distance between mid-pedicles	7.2 cm.	7.9 cm.	10

and the unfused area (six undamaged epiphyseal plates) between the third lumbar and the first sacral vertebrae increased as follows:

	12/16/52	7/9/58	Increase (per cent)
Distance between mid-bodies	6.7 cm.	8.7 cm.	30
Distance between mid-pedicles	6.0 cm.	8.0 cm.	33

By the method of Hallock, Francis, and Jones, the fused healthy vertebrae, measured from the top of the ninth thoracic to the bottom of the eleventh thoracic vertebra and from the top of the second lumbar to the bottom of the third lumbar vertebra, increased as follows:

	12/16/52	7/9/58	Increase (per cent)
T9 to T11	4.7 cm.	5.6 cm.	19
L2 to L3	4.0 cm.	4.9 cm.	22

and the unfused healthy vertebrae, measured from the top of the fourth lumbar vertebra to the bottom of the first sacral vertebra, increased as follows:

L4 to S1	6.0 cm.	8.0 cm.	33 (per cent)

Similarly, by their method, the total fusion area, measured both from the top of the ninth thoracic to the bottom of the third lumbar vertebra and from the superior margin of the pedicle of the ninth thoracic to the inferior margin of the pedicle of the third lumbar vertebra, increased as follows:

	12/16/52	7/9/58	Increase (per cent)
Bodies, T9 to L3	12.0 cm.	13.7 cm.	14
Pedicles, T9 to L3	12.2 cm.	13.5 cm.	11

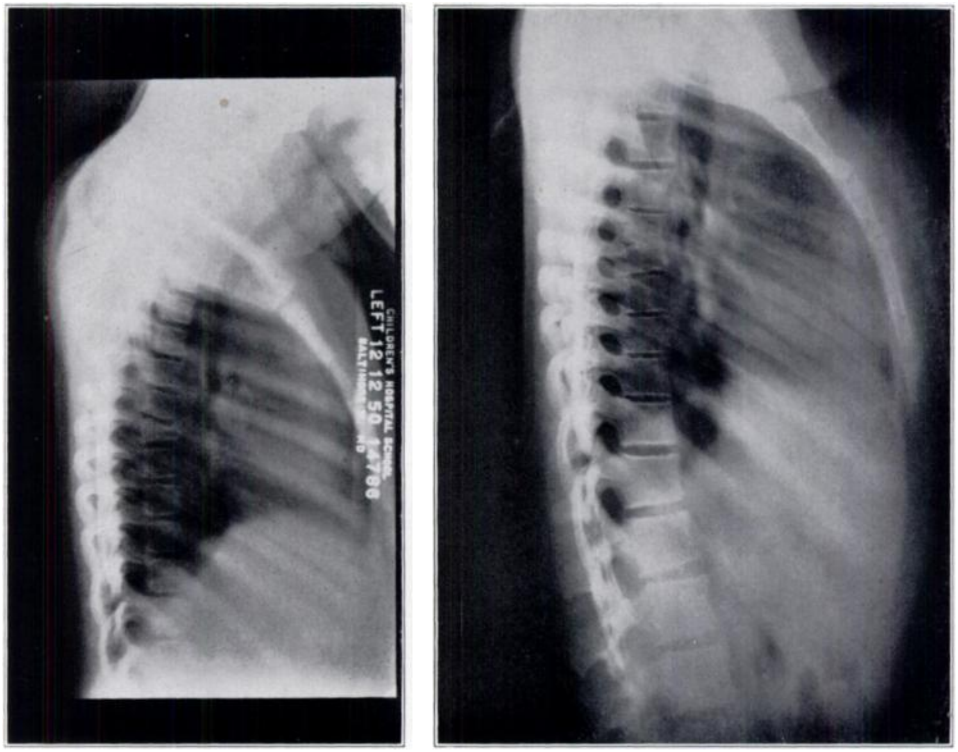

FIG. 5-A FIG. 5-B

Case D. R., tuberculosis of the spine involving the fifth and sixth thoracic vertebrae.

On June 16, 1950, a massive Hibbs fusion, reinforced with ribbon grafts from the tibia, was performed from the fourth to the tenth thoracic vertebra.

Roentgenograms at yearly intervals thereafter indicated that the graft was solid throughout its entire extent. The roentgenograms used for measurement were obtained on December 12, 1950, when the patient was eight years old (Fig. 5-A), and on June 2, 1955, when the child was twelve and a half (Fig. 5-B).

Using these roentgenograms, we determined the increase in height of the fused and the unfused normal vertebrae, employing first our method and then that of Hallock, Francis, and Jones.

By our method the fused area (six undamaged epiphyseal plates) between the fifth and ninth thoracic vertebrae increased as follows:

	12/12/50	6/2/55	Increase (per cent)
Distance between mid-bodies	7.3 cm.	8.1 cm.	11
Distance between mid-pedicles	7.5 cm.	8.0 cm.	7

and the unfused area (six normal epiphyseal plates) between the tenth thoracic and the first lumbar vertebrae increased as follows:

	12/12/50	6/2/55	Increase (per cent)
Distance between mid-bodies	7.4 cm.	10.4 cm.	41
Distance between mid-pedicles	7.8 cm.	11.0 cm.	41

By the method of Hallock, Francis, and Jones, the fused healthy vertebrae, measured from the top of the seventh thoracic to the bottom of the tenth thoracic vertebra, increased as follows:

T7 to T10	7.8 cm.	9.4 cm.	21 (per cent)

and the unfused normal vertebrae, measured from the top of the eleventh thoracic to the bottom of the first lumbar vertebra, increased as follows:

T11 to L1	7.2 cm.	10.2 cm.	42 (per cent)

Similarly, by their method, the total fusion area, measured both from the top of the fourth thoracic to the bottom of the tenth thoracic vertebra and from the superior margin of the pedicle of the fourth thoracic to the inferior margin of the pedicle of the tenth thoracic vertebra, increased as follows:

	12/12/50	6/2/55	Increase (per cent)
Bodies, T4 to T10	12.6 cm.	15.1 cm.	20
Pedicles, T4 to T10	12.5 cm.	14.4 cm.	15

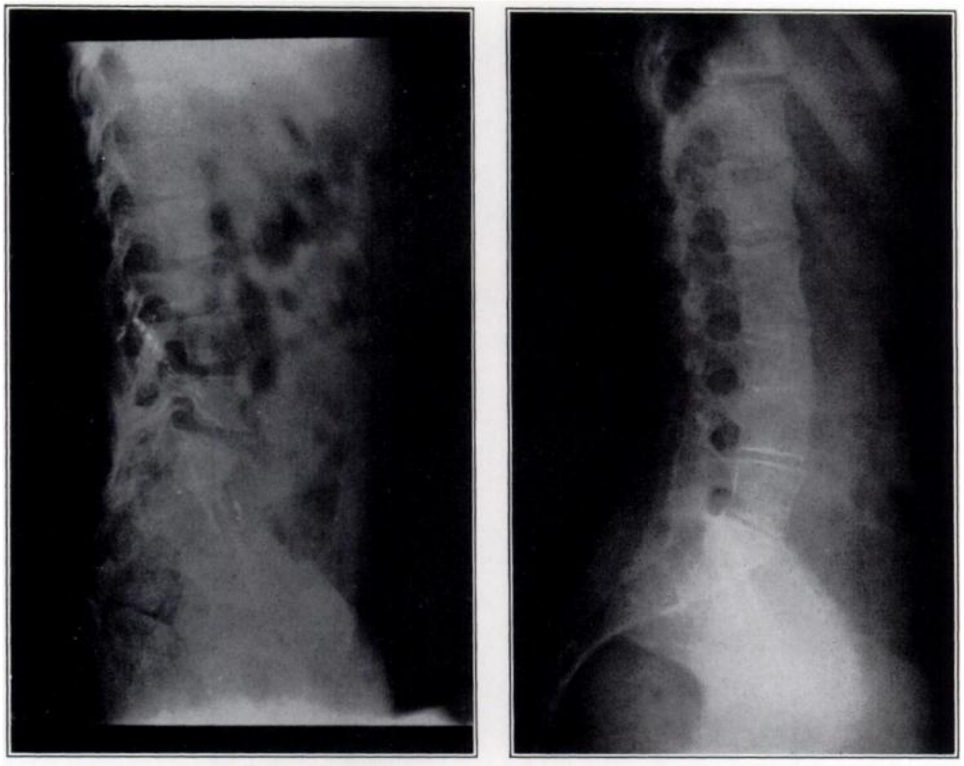

FIG. 6-A FIG. 6-B

Case B. A. S., tuberculosis of the spine involving the third and fourth lumbar vertebrae. On February 17, 1950, a spine fusion from the first lumbar to the fifth lumbar vertebra was attempted, but pseudarthroses developed between the third and fourth and between the fourth and fifth lumbar vertebrae. On February 9, 1951, these pseudarthroses were repaired successfully. However, a pseudarthrosis that had been overlooked in several roentgenograms was subsequently seen between the first and second lumbar vertebrae.

Yearly roentgenograms thereafter revealed that the graft was solid from the second lumbar to the second sacral vertebra. The roentgenograms used for measurement by both our method and that of Hallock, Francis, and Jones were obtained on June 15, 1951, when the child was seven years old (Fig. 6-A), and on April 11, 1958, when the child was fourteen (Fig. 6-B).

By our method the fused area (four undamaged epiphyseal plates) between the fourth lumbar and first sacral vertebrae increased as follows:

	6/15/51	4/11/58	Increase (per cent)
Distance between mid-bodies	5.7 cm.	6.2 cm.	9
Distance between mid-pedicles	4.9 cm.	5.3 cm.	8

and the unfused area (four normal epiphyseal plates) between the eleventh thoracic and the first lumbar vertebrae increased as follows:

	6/15/51	4/11/58	Increase (per cent)
Distance between mid-bodies	5.2 cm.	7.3 cm.	40
Distance between mid-pedicles	5.5 cm.	7.3 cm.	33

By the method of Hallock, Francis, and Jones, the fused healthy vertebrae, measured from the top of the second lumbar to the bottom of the third lumbar vertebra, increased as follows:

L2 to L3	4.8 cm.	6.2 cm.	29 (per cent)

and the unfused normal vertebrae, measured from the top of the twelfth thoracic to the bottom of the first lumbar vertebra, increased as follows:

T12 to L1	4.8 cm.	6.8 cm.	42 (per cent)

Similarly, by their method, the total fusion area, measured both from the top of the second lumbar to the bottom of the first sacral vertebra and from the superior margin of the pedicle of the second lumbar to the inferior margin of the pedicle of the first sacral vertebra, increased as follows:

	6/15/51	4/11/58	Increase (per cent)
Bodies, L2 to S1	12.5 cm.	15.0 cm.	20
Pedicles, L2 to S1	11.5 cm.	13.5 cm.	17

FIG. 7-A

FIG. 7-B

Case M.L., tuberculosis of the spine involving the third, fourth, and fifth lumbar vertebrae.

An Albee fusion from the first lumbar to the first sacral vertebra was attempted on August 14, 1942, when the patient was four years old. Pseudarthroses developed between the second and third and between the third and fourth lumbar vertebrae. These pseudarthroses were repaired on January 26, 1943.

Yearly roentgenograms thereafter revealed the fusion to be solid from the first lumbar to the second sacral vertebra. The roentgenograms used for measurement by both our method and that of Hallock, Francis, and Jones were obtained on July 1, 1943, when the patient was five years old (Fig. 7-A), and on August 25, 1949, when the child was eleven (Fig. 7-B).

By our method, the fused area (four undamaged epiphyseal plates) between the second lumbar and first sacral vertebrae increased as follows:

	7/1/43	8/25/49	Increase (per cent)
Distance between mid-bodies	6.2 cm.	6.8 cm.	10
Distance between mid-pedicles	6.3 cm.	6.9 cm.	10

and the unfused area (four normal epiphyseal plates) between the tenth and twelfth thoracic vertebrae increased as follows:

	7/1/43	8/25/49	Increase (per cent)
Distance between mid-bodies	4.2 cm.	5.9 cm.	40
Distance between mid-pedicles	4.3 cm.	5.8 cm.	35

By the method of Hallock, Francis, and Jones the fused healthy vertebrae, measured from the top of the first lumbar to the bottom of the second lumbar vertebra, increased as follows:

L1 to L2	4.5 cm.	6.0 cm.	33 (per cent)

and the unfused normal vertebrae, measured from the top of the tenth to the bottom of the twelfth thoracic vertebra, increased as follows:

T10 to T12	6.0 cm.	8.5 cm.	42 (per cent)

Similarly, by their method, the total fusion area, measured both from the top of the first lumbar to the bottom of the first sacral vertebra and from the superior margin of the pedicle of the first lumbar to the inferior margin of the pedicle of the first sacral vertebra, increased as follows:

	7/1/43	8/25/49	Increase (per cent)
Bodies, L1 to S1	10.5 cm.	12.3 cm.	17
Pedicles, L1 to S1	10.0 cm.	11.5 cm.	15

FIG. 8-A

FIG. 8-B

Case G.N., tuberculosis of the spine involving the sixth, seventh, and eighth thoracic vertebrae. A two-stage (the first on December 8, 1950, and the second on January 26, 1951) Hibbs fusion from the third thoracic to the twelfth thoracic vertebra was attempted, using bank bone. Fusion was solid from the third to the eleventh thoracic vertebra, as evidenced by a roentgenogram made in April 1951, but there was pseudarthrosis between the eleventh and twelfth thoracic vertebrae.

Roentgenograms were obtained frequently during the following two years. However, there was then a two-year lapse; the next roentgenogram was not made until 1955. At this time there was evidence that the pseudarthrosis had healed spontaneously, without treatment. Measurements by both our method and that of Hallock, Francis, and Jones were made on the basis of the initially solid fusion extending from the third to the eleventh thoracic vertebra. The roentgenograms used were obtained on August 6, 1951, when the patient was five years old (Fig. 8-A), and on June 7, 1955, when the child was nine (Fig. 8-B). In the interval between these roentgenograms the kyphosis had diminished slightly.

By our method, the fused area (eight undamaged epiphyseal plates) between the fourth and tenth thoracic vertebrae had increased as follows:

	8/6/51	6/7/55	Increase (per cent)
Distance between mid-bodies	8.5 cm.	8.7 cm.	2
Distance between mid-pedicles	10.0 cm.	10.2 cm.	2

and the unfused area (eight normal epiphyseal plates) between the first and fifth lumbar vertebrae had increased as follows:

	8/6/51	6/7/55	Increase (per cent)
Distance between mid-bodies	10.5 cm.	12.2 cm.	16
Distance between mid-pedicles	9.9 cm.	11.0 cm.	11

By the method of Hallock, Francis, and Jones, the fused healthy vertebrae, measured from the top of the ninth thoracic to the bottom of the eleventh thoracic vertebra and from the top of third thoracic to the bottom of the fifth thoracic vertebra, increased as follows:

	8/6/51	6/7/55	Increase (per cent)
T9 to T11	5.3 cm.	6.0 cm.	13
T3 to T5	4.7 cm.	5.2 cm.	11

and the unfused normal vertebrae, measured from the top of the first lumbar to the bottom of the third lumbar vertebra, increased as follows:

L1 to L3	7.1 cm.	8.1 cm.	14 (per cent)

Similarly, by their method, the total fusion area, measured both from the top of the third thoracic to the bottom of the eleventh thoracic vertebra and from the superior margin of the pedicle of the third thoracic to the inferior margin of the pedicle of the eleventh thoracic vertebra, increased as follows:

	8/6/51	6/7/55	Increase (per cent)
Bodies, T3 to T11	12.0 cm.	12.9 cm.	7
Pedicles, T3 to T11	13.1 cm.	14.0 cm.	7

FIG. 9-A

FIG. 9-B

Case W. R., tuberculosis of the spine involving the fourth and fifth lumbar vertebrae.

On February 4, 1949, a Hibbs fusion, reinforced with tibial bone, was performed from the first lumbar to the second sacral vertebra. Fusion became solid from the second lumbar to the second sacral vertebra, with pseudarthrosis between the first and second lumbar vertebrae.

Thereafter, roentgenograms were obtained at least once yearly until 1955. The roentgenograms used for measurement by both our method and that of Hallock, Francis, and Jones were obtained on June 7, 1949, when the patient was seven years old (Fig. 9-A), and on June 6, 1955, when the child was thirteen (Fig. 9-B).

By our method, the fused area (four undamaged epiphyseal plates) between the third lumbar and first sacral vertebrae increased as follows:

	6/7/49	6/6/55	Increase (per cent)
Distance between mid-bodies	6.7 cm.	7.1 cm.	6
Distance between mid-pedicles	6.2 cm.	6.4 cm.	3

and the unfused area (four normal epiphyseal plates) between the tenth and twelfth thoracic vertebrae increased as follows:

	6/7/49	6/6/55	Increase (per cent)
Distance between mid-bodies	5.1 cm.	6.5 cm.	25
Distance between mid-pedicles	5.3 cm.	6.8 cm.	28

By the method of Hallock, Francis, and Jones, the fused healthy vertebrae, measured from the top of the second lumbar to the bottom of the third lumbar vertebra, increased as follows:

	6/7/49	6/6/55	Increase (per cent)
L2 to L3	5.5 cm.	6.7 cm.	22

and the unfused normal vertebrae, measured from the top of the tenth thoracic to the bottom of the twelfth thoracic vertebra, increased as follows:

T10 to T12	7.0 cm.	9.1 cm.	30 (per cent)

Similarly, by their method, the total fusion area, measured both from the top of the second lumbar to the bottom of the first sacral vertebra and from the superior margin of the pedicle of the second lumbar to the inferior margin of the pedicle of the first sacral vertebra, increased as follows:

	6/7/49	6/6/55	Increase (per cent)
Bodies, L2 to S1	11.7 cm.	12.8 cm.	9
Pedicles, L2 to S1	10.3 cm.	11.0 cm.	7

Epiphyseal growth will be suppressed in an area of increased pressure and more active in an area of decreased pressure—according to the Hueter-Volkmann law—thus allowing bending through growth. But the shaft of a long bone or a long fusion plate responds to Wolff's law, which states that increased pressure causes increased bone formation and consequent greater strength of the bone in the area of stress, with the result that bending does not occur. There is, however, another law. Weinmann and Sicher stated that: "Increase of pressure or tension beyond the limits of tolerance leads to destruction of bone by resorption". This obviously occurs with pressure caused by certain tumors and aneurysms. Could not this also be true in spine fusions, in which excessive tension, due to growth, or excessive pressure, due to overcorrection of scoliosis, may produce resorption of bone sufficient to cause an actual loss of continuity of the graft in one area? This loss of continuity, pseudarthrosis, or stress fracture—call it what you will —may then allow stretching or bending of the graft.

CLINICAL INVESTIGATION

This study was initiated because of the clinical problem of young children requiring long spine fusions for such diverse reasons as idiopathic scoliosis, tuberculosis, poliomyelitis, and congenital anomalies. It is certainly important, before subjecting a small child to such an operation, to know the long-term, as well as the short-term effects of the procedure. An accurate knowledge of bone growth after fusion is essential to evaluate whether, in a given situation, the desirable effects of the operation will outweigh any possible long-term undesirable effects. Such knowledge is also vital in determining the extent and, perhaps, the type of fusion.

Although the recent majority opinion, as expressed in the literature, seems to be that growth still persists after fusion, at a slower but a substantial rate, it seemed to us that this concept is contrary to the basic laws of bone physiology. Therefore, it was decided to evaluate the clinical material at the Children's Hospital and the Kernan Hospital for Crippled Children, both in Baltimore, to see what happened in actual situations. A wealth of clinical material was available and there were many long-term follow-ups.

Attempts to determine the growth of the fusion mass after spine fusion for scoliosis were unrewarding. It is almost impossible to judge by roentgenogram the solidity of a fusion in a thoracic spine with scoliosis. Furthermore, if the curvature and rotation are significant, accurate measurement of the length of the fusion area is extremely difficult.

Hibbs and Albee fusions for tuberculosis of the spine in children under ten years of age were next studied. Roentgenograms of the spines of 400 children with tuberculosis of the spine were available in the two hospitals, yet it was amazing how few could be properly evaluated with respect to bone growth after fusion. In many cases, it was extremely difficult to judge the solidity of the fusion, especially the Hibbs fusion in the thoracic region. In spines in which the fusion plate could be clearly seen, the incidence of pseudarthrosis in one or more areas was almost 75 per cent. Often, these pseudarthroses were near the ends of the fusion and they often healed spontaneously, as shown by later roentgenograms. These defects did not seem to interfere greatly with the healing of the tuberculosis, but they did interfere with growth evaluation. Many cases had incomplete follow-up roentgenograms and records. Finally, the long-term follow-up roentgenograms—twenty years or more after fusion—seemed so grossly magnified and of such different technique that it was extremely difficult to make accurate comparisons.

With these problems in mind, it was decided to review the paper by Hallock, Francis, and Jones more closely, since this is the only one that gives in detail the criteria and techniques used for growth measurements after spine fusion.

Their patients were all treated by Hibbs fusion; no mention is made of additional bone grafts being taken from other areas. Seven fusions were in the thoracic area, and eight were in thoracolumbar or lumbar areas. Kyphosis was moderate to moderately severe in thirteen of fifteen patients, thus making accurate measurement difficult. They stated that fusion was successful in all patients but they did not mention what roentgenographic criteria were used to determine this, or if the presence of fusion was verified by surgical exploration. Measurements were made from "early postoperative" roentgenograms, but the exact time after operation was not stated.

Their measurements were of the normal vertebrae included within the extent of the fusion and of the whole fusion area. The normal vertebrae, usually two above or below the diseased area, were measured from the top of the top vertebral body to the bottom of the bottom vertebral body (as from *1* to *4* in Fig. 1). Thus, the end one of the four epiphyseal plates included in the region measured (Fig. 1, *1*) is completely unaffected by the fusion, and hence at least 25 per cent of the normal growth of the segments being measured could be expected to occur. At the other end of the measured segments (Fig. 1, *4*), the disc space in the roentgenograms of older patients is markedly narrowed, as noted by Hallock, Francis, and Jones, and this narrowing probably occurs because of bone replacement of the disc material. At any rate, the disc space is largely replaced by the adjacent vertebral bodies and any measurement using the vertebral end-plate in this way would show growth of the individual vertebral body, but this growth may be at the expense of the disc and does not indicate growth of the fused segment as a whole.

Measurement of the whole fused area (Fig. 1, from *1* to *10* or from *1* to *12*, depending on the length of fusion) will include two growth plates (two out of ten or twelve) that are not restricted by the fusion. Hence, 15 to 20 per cent of the normal growth of these six or seven fused vertebrae will take place anyway, not in the least influenced by the fusion. Measurement of the distance between the pedicles is subject to the same consideration, although to a lesser degree. The uppermost or lowermost pedicles are free to grow in width, especially if the adjacent vertebral body grows and pulls the periosteum of the pedicles with it. In a fused area the bone of the pedicle may expand somewhat at the expense of adjacent ligaments.

The presence of pseudarthrosis was never mentioned as a possibility by Hallock, Francis, and Jones. In our series, numerous defects in the fusion plates were found on close examination. Sometimes, these were not visible in one roentgenogram, especially the one made early after operation, but were found on subsequent roentgenograms. In other instances they were present in the early roentgenograms, but subsequently healed spontaneously (Fig. 2). A study of numerous roentgenograms of the same fusion over a long period of time is necessary to rule out adequately either the presence or the absence of defects in the fusion.

Finally, the ages of the children in the early postoperative roentgenograms are not given by Hallock, Francis, and Jones. Presumably, these children were from four to six years old and probably weighed about fifty pounds. The average follow-up was twenty-one years; hence, the follow-up roentgenograms used for comparison were of adults who presumably weighed about 150 pounds. The magnification factor to be expected from these, if the tube-to-target distances were the same (thirty-six inches), would be 17 per cent (Fig. 3).

To illustrate, let us suppose that a fused area during growth increases from 2.8 to 3.4 centimeters and an unfused area from 2.4 to 4.1 centimeters, as shown by roentgenograms made first when the patient was a small child and later when he was an adult. By using the correction factors shown in Figure 3, the childhood measurements are enlarged 11 per cent. When corrected, these will be changed from 2.8 to 2.52 centimeters and from 2.4 to 2.16 centimeters. The adult measurements are enlarged 28 per cent and hence, when corrected, will be changed from 3.4 to 2.65 centimeters and from 4.1 to 3.2 centimeters. Thus, after correction for magnification, we find that the fused area has grown from 2.52 to 2.65 centimeters, or 4 per cent growth, and the unfused area from 2.16 to 3.2 centimeters, or 45 per cent growth. Now, 0.13 centimeter, or 4 per cent growth, is statistically insignificant and well within the limits of error in measurement, so for practical purposes no significant growth has taken place in the fused area, and about 45 per cent growth has taken place in the unfused area.

Using these same figures Hallock, Francis, and Jones estimated that the fusion area grew 120 per cent, a change of 20 per cent, and that the normal area grew 170 per cent, a change of 70 per cent. Using these values, these authors calculated the growth by subtracting one value from the other. The result was 50 per cent less growth in the fusion area; whereas, in point of fact, there is no real evidence that the fusion area grew at all. The only evidence provided by these figures is that the unfused portion grew somewhat in comparison with the fused area.

METHOD

In our series an attempt was made to avoid the variable factors just mentioned by setting up a rigid set of criteria. First to be included was that a solid fusion plate had to be clearly visible on the roentgenograms. This ruled out most Hibbs fusions, unless extensive new bone had been added. Albee operations in the lumbar and thoracolumbar area were the most easily evaluated. All cases with pseudarthroses in the measured area were discarded, and no cases were considered unless the fusion plate was clearly visible throughout the measured area.

The second criterion was that the first measurement should not be made until at least four months after surgery. A graft takes several months to become solidly incorporated; growth may occur during this interval. An Albee graft, in particular, may look solid shortly after surgery but may break down later. A spine measured shortly after surgery and again many years later may look solid on both sets of roentgenograms and yet have had numerous pseudarthroses in the interval.

The third criterion was that all patients should have had numerous roentgenograms, preferably once a year, during the period of measurement to be sure that the fusion had remained solid the entire time. This requirement was instituted because a number of cases were found in which pseudarthroses had developed and then had healed spontaneously and also because some roentgenograms for technical reasons showed no defects, whereas other roentgenograms made before and after these had demonstrated defects.

The fourth criterion was that the fusion area to be measured should include at least four undamaged vertebral epiphyseal plates, all well within the limits of the fusion mass, and that the length of this fused area be compared with that of an unfused portion of the spine containing an equal number of growth plates. The fused area being measured should not contain an end vertebra since such a measurement would include the growth of an end-plate unrestrained by the fusion. Furthermore, no measurements should be made from the end-plates since measurements from these points of reference might include the unrestrained growth of the top and bottom vertebral plates which takes place at the expense of the adjacent intervertebral discs. Instead, measurements should be made from the mid-points of the top and bottom vertebral bodies since these points would be expected to remain relatively constant with bone replacement of the intervertebral discs above and below these central points being about equal (Fig. 1). These measurements sometimes spanned the disease area, but the disease was quiescent in all cases and restitution of the involved area, rather than further destruction, was the rule.

Measurements of the posterior elements were made from the mid-points of the pedicles, as visualized in the lateral roentgenogram rather than from the upper and lower borders of the pedicles. In the absence of markers other posterior measurements were grossly inaccurate, and even these measurements between the pedicles were not so accurate as those between the centers of the vertebral bodies.

The fifth criterion was that the follow-up period should be long enough to show significant growth in the unfused areas, but not too long, because the physique of the child may change radically and cause gross differences in the magnification of the roentgenograms. Only roentgenograms made in the modern era (since 1940) were used to make sure that the roentgenographic techniques were fairly well standardized. Spines with excessive kyphoses or scolioses were avoided, since these deformities make measurement difficult; only one of the cases finally accepted for study had more than a mild kyphosis. A range of follow-up of from four to eight years was approved since, with yearly roentgenograms made during this interval, it was possible to follow the gradual growth of the spine and thus avoid undue distortion. Undoubtedly, some degree of magnification occurred and the roentgenographic techniques and positioning of the patient were not completely standardized, but the roentgenograms were as nearly comparable as could be obtained without some constant factor, such as a one-centimeter metal marker embedded in the graft. It is hoped that future series will be conducted with such a marker system to avoid the variable factors that render interpretation so difficult at present.

These criteria were so exacting that it was necessary to discard, for one reason or another, the great majority of cases reviewed. It was possible finally to collect only six cases from the two hospitals which fulfilled all the criteria mentioned. These cases were measured by our own system and also by that of Hallock and associates. The results of these measurements are recorded in the legends for the reproduction of the roentgenograms used in this study. The photographs of the roentgenograms were made at the same distance and magnification for each pair so that measurements of these photographs should give the same percentage differences as the original roentgenograms.

RESULTS

The average percentages of growth of the fused and unfused vertebrae in the six cases studied were determined by two methods.

1. Our criteria: mid-body measurements of the fusion area, 8 per cent; mid-body measurements of the normal area, 32 per cent; mid-pedicle measurements of the fusion area, 7 per cent; and mid-pedicle measurements of the normal area, 30 per cent.

2. Hallock, Francis, and Jones' criteria: normal fused vertebrae, measured from the top of the top vertebra to the bottom of the bottom vertebra, 21 per cent; normal unfused vertebrae, measured from the top of the top vertebra to the bottom of the bottom vertebra, 34 per cent; total fusion area, measured from

the top of the top vertebra to the bottom of the bottom vertebra, 14 per cent; and total fusion area measured from the superior margin of the pedicle of the top vertebra to the inferior margin of the pedicle of the bottom vertebra, 12 per cent.

It is apparent that even without any correction for magnification or distortion, the growth, as measured by our criteria, was only 25 per cent as much by the mid-body measurements and 23 per cent as much by the mid-pedicle measurements in the fused areas as in the unfused areas. With the criteria of Hallock and associates used for the measurement of these same spines, the normal vertebrae included in the fusion grew 62 per cent as much as the normal vertebrae outside the fusions. The whole fusion area from top to bottom grew 41 per cent as much anteriorly in the vertebral bodies and 35 per cent as much in the region of the pedicles as did the adjacent unfused areas.

Hallock, Francis, and Jones did not specifically state that the rate of growth in the fused area was a certain percentage of the normal rate. However, their statement that the vertebral bodies of the entire fusion area grew 37 per cent less than the normal vertebral bodies seems to imply that the vertebral bodies within the fused area grew 63 per cent as much as the normal vertebral bodies. Similarly, if the normal vertebral bodies within the fusion area grow 23 per cent less than normal vertebral bodies, the inference is that their growth was 77 per cent of the normal. We believe that in future studies of vertebral growth every effort should be made to reduce distortion and magnification to a minimum and then make a direct comparison, admitting that a certain degree of inaccuracy still persists.

The cases in this series are not directly comparable with those in the series studied by Hallock and associates in that the follow-up period in our series is shorter (for reasons mentioned previously). However, the percentage of growth should be relatively comparable, whether the follow-up is five or fifteen years. When Hallock, Francis, and Jones' technique for the measurement of vertebral growth was used in this series, the amount of growth of the vertebral bodies in the whole fusion area was 41 per cent of normal. In the series reported by Hallock and associates, the amount of growth in the fused area of their patients was, by inference, 63 per cent of normal. Similarly, the amount of growth of the normal vertebral bodies included in the fusion area was 62 per cent of normal in our series and 77 per cent of normal, by inference, in the series studied by Hallock, Francis, and Jones.

Although these results are not too far apart, the rate of growth in our series was definitely smaller than that in the other series. We believe that the explanation for this difference is that intercurrent pseudarthroses have been carefully excluded in our cases. Among the fifteen cases studied by Hallock and associates, the amount of growth of the fused normal vertebrae was 100 per cent of normal in two, less than 50 per cent in three, and between 50 and 100 per cent in the remaining cases. This rather wide variation in the amount of growth in one series suggests some difference in the restraining force exerted by the fusion plate—a difference that could well be explained by unrecognized transitory pseudarthroses.

SUMMARY AND CONCLUSIONS

It was concluded from these cases that when a spine fusion is unquestionably solid and fairly massive, there is little increase in length of the fused area. The small increase that most of the cases we studied showed could be accounted for by magnification and other technical factors, but it is impossible to rule out a small amount of growth. The slight decrease in the kyphos in two of our cases suggests some bending of the fusion mass. No definite pseudarthroses could be seen on the roentgenograms but the presence of one or more pseudarthroses could not be ruled out. Microscopic and transient pseudarthroses are considered by us to be the most likely mechanism by which any real increase in length or any true change in angulation occurs. In our experimental studies [9], microscopic losses of bone continuity in transepiphyseal bone grafts in the distal femora of young rabbits were demonstrated. These defects were of such a nature that they could not be demonstrated by standard clinical or roentgenographic methods.

In our opinion, the end-result study of Hallock and his associates is valuable in that it indicates, from the practical, clinical point of view, what will happen to the average patient after spine fusion in early childhood. However, their data and the observations of the other authors previously mentioned convey an inaccurate and perhaps unintentional impression that considerable growth occurs in a solidly fused spine segment. It would be unfortunate, we believe, to allow this impression to persist since surgeons not familiar with all that is known about growth of the spine after spine fusion might be falsely encouraged on the basis of published data to perform longer and more massive spine fusions in young children. Our study suggests that a long, massive, and completely solid fusion in early childhood will impair spine growth to a significant degree.

We believe that growth of a fused segment of the spine can occur only at the ends of the segment or at the site of gross or microscopic defects in the fusion plate. Pseudarthroses in spine fusions in children are much more frequent, in our opinion, than is generally suspected because of the tension forces exerted by the growing epiphyseal cartilages, as well as the usual stresses caused by motion. These pseudarthroses or stress fractures may be microscopic or grossly visible; they may occur spontaneously at any time and heal spontaneously. The more massive the fusion plate, the less chance there will be that it will break down under the stress of growth and motion. Finally, we believe that the laws that govern bone growth in general apply to the bone of spine fusions. There is in our opinion no such thing as interstitial growth of bone.

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