Chapter 1

A BRIEF REVIEW OF COMPUTER ASSISTED SURGERY
WITH SPECIAL REFERENCE TO PEDICLE SCREW PLACEMENT

1.1 INTRODUCTION

Pedicle screw fixation techniques are usually used in the case of vertebral fractures, dislocations, scoliosis, kyphosis, spinal tumors, failed previous fusions (pseudarthrosis) and for the severe back pain that doesn't respond to other therapies. The biggest challenge in the surgery is accurate placement of the pedicle screws. Pedicle screws have been used in increasing numbers for numerous indications ever since their popularization by Roy-Camille. Spinal fusion rates are significantly greater with pedicle screws. But difficulty in assessing correct pedicle screw position by conventional roentgenography is well recognized. Concerns have arisen about the incidence and consequences of screw misplacement in the thoracic and lumbosacra areas. Significant rates of unrecognized screw misplacement and permanent nerve root damage have been documented.

In this dismal background, attempts at computer assisted pedicle screw fixation have gained much importance and reports from research work done in many centers in the world, is showing high accuracy rates. The prohibitive cost and non-availability of these gadgets developed by these centers, limit their use in countries like India. Hence a software and hardware were
developed indigenously for computer assisted pedicle screw fixation and the total cost of the system was much less when compared to other systems available.

1.2 ADVANTAGES

Computer assisted pedicle screw placement has got high accuracy rate. Unrecognized screw misplacement and permanent root damage have been documented with conventional fluoroscopic- technique. Computer assisted technique has got much advantage in deformed and pediatric spine where anatomical landmarks are ill-defined. Computer Assisted simulations and surgical procedures done on bone models are excellent training tools.

1.3 DESIGN & DEVELOPMENT OF SOFTWARE

Computer Assisted Spine Surgery has become popular throughout the world in recent times because of the greater accuracy and precision offered by the software. The surgeon can get real time feedback during surgery even when he is operating in inaccessible areas of the spine. There are more than 10 system manufactures with different softwares for spine surgery. But the cost of these systems for computer assisted orthopaedic surgery is prohibitively expensive even in well developed rich countries. The advantages of compute assisted surgery cannot be enjoyed by the poor people of our country because of the very high cost and non-availability of these systems in our ordinary hospitals.
Hence a research work was taken up in the department of orthopaedics, Medical College, Kottayam under the guidance of Prof. P S John to develop a system for performing computer assisted pedicle screw placement. Technical advice and help from many computer experts and engineers was received for developing an indigenously developed software for computer assisted pedicle screw placement at a very low cost. The research project was started in the year 1996 and bone model experiments were done from 1998. The software was used for experimental surgery on cadavers from 2000 onwards. With the excellent results in bone model and cadaveric studies, the software was used for the first time clinically in November 2002. This was the first case of computer assisted spine surgery reported from India. Thereafter more than 100 pedicle screw fixations were done and the results were comparable to other more expensive systems. Our results were presented in 6 international conferences and published in 5 international publications. Over the years many modifications and refinements were done to improve the accuracy of the software. Research is still continuing to make it available throughout India at a very low price, affordable to any patient.

During the period of the thesis work the software was refined and its accuracy was tested in Cadaveric studies and clinical studies. The modification and refinement of the software was done in with help of the department of Pure & Applied Physics, Mahatma Gandhi University, Kottayam under the guidance of Prof. C. S. Menon.
The normal anatomy of the spine is usually described by dividing up the spine into 3 major sections: the cervical, the thoracic, and the lumbar spine. (Below the lumbar spine is a bone called the sacrum, which is part of the pelvis). Each section is made up of individual bones called vertebrae. There are 7 cervical vertebrae, 12 thoracic vertebrae, and 5 lumbar vertebrae.

An individual vertebra is made up of several parts. The body of the vertebra is the primary area of weight bearing and provides a resting place for the fibrous discs which separate each of the vertebrae. The lamina covers the spinal canal, the large hole in the center of the vertebra through which the spinal nerves pass. The spinous process is the bone you can feel when running.
your hands down your back. The paired transverse processes are oriented 90 degrees to the spinous process and provide attachment for back muscles.

There are four facet joints associated with each vertebra. A pair that face upward and another pair that face downward. These interlock with the adjacent vertebrae and provide stability to the spine. The vertebrae are separated by intervertebral discs which act as cushions between the bones.

Each disc is made up of two parts. The hard, tough outer layer called the annulus surrounds a mushy, moist center termed the nucleus.

![Spinal Column viewed from back](image_url)

**Figure 2**: Spinal Column viewed from back
When a disc herniates or ruptures, the soft nucleus spurts out through a tear in the annulus, and can compress a nerve root. The nucleus can squirt out on either side of the disc or in some cases both sides. The amount of pain associated with a disc rupture often depends upon the amount of nucleus that breaks through the annulus, and whether it compresses a nerve. To help alleviate the pain, a Laminotomy/Microdiscectomy may be performed.

**Spine Anatomy and Spine General**

The purpose of the spine is to help us stand and sit straight, move, and provide protection to the spinal cord.

*Figure 3: Attitude of the spine in different situations*
The human spine has 7 Cervical vertebra (C), 12 Thoracic vertebra (T), 5 Lumbar vertebra (L), and 5 Sacral vertebra (S). Generally, these are numbered in the following manner: the first cervical vertebra is C1 and the last cervical vertebra is C7. The first thoracic vertebra is T1 and the last thoracic vertebra is T12. Similarly, the first lumbar vertebra is L1 and the last lumbar vertebra is L5. After the L5 vertebra is the sacrum and although there are 5 sacral vertebra, there typically are no discs intervening here. Between the second cervical vertebra and the first sacral vertebra are intervening discs. The discs are structures made out of cartilage and they provide cushion between each vertebral segment. The discs are then referred to by the vertebra which borders them: the disc between the fifth lumbar vertebra and the first sacral vertebra is the L5,S1 disc, the disc between the fifth and sixth cervical vertebra is the C5,6 disc. Please note, that there are individuals born with either one extra or one less vertebra and this may alter the numbering system at times.

Further, each vertebra joins the above and below vertebra with many different types of joints. Typically each vertebra has 4 facet joints: a right and left superior and inferior facet. The cervical vertebra also have 2 joints which are called uncovertebral joints. Between the first and second cervical vertebra, there is a special joint which allows rotation of the head. The first and second vertebra are thus extremely unique and do not follow most of the typical anatomical rules.
Since the spine helps us to stand straight, its shape is designed to carry the weight of the body and distribute it straight down through the pelvis. Each individual segment of the spine also has its unique curvature. The cervical curvature is called the cervical lordosis (backward bend), the thoracic curvature is called the thoracic kyphosis (forward bend), and the lumbar curvature is called the lumbar lordosis (backward bend).

![Cervical Spine Diagram]

Figure 4: Cervical Spine (Neck)
Spine image 1 is a front view of the spine and the spinal elements. Spine image 2 is a left sided side view and Spine image 3 is a view of the spine from the back.

**General Characteristics of a Vertebra**

A typical vertebra consists of two essential parts—viz., an anterior segment, the body, and a posterior part, the vertebral or neural arch; these enclose a foramen, the vertebral foramen. The vertebral arch consists of a pair of pedicles and a pair of laminae, and supports seven processes—viz., four articular, two transverse, and one spinous.

*Figure 5: A typical thoracic vertebra, viewed from above*
When the vertebrae are articulated with each other the bodies form a strong pillar for the support of the head and trunk, and the vertebral foramina constitute a canal for the protection of the medulla spinalis (spinal cord), while between every pair of vertebrae are two apertures, the intervertebral foramina, one on either side, for the transmission of the spinal nerves and vessels.

Body (corpus vertebrae) — The body is the largest part of a vertebra, and is more or less cylindrical in shape. Its upper and lower surfaces are flattened and rough, and give attachment to the intervertebral fibrocartilages, and each presents a rim around its circumference. In front, the body is convex from side to side and concave from above downward. Behind, it is flat from above downward and slightly concave from side to side. Its anterior surface presents a few small apertures, for the passage of nutrient vessels; on the posterior surface is a single large, irregular aperture, or occasionally more than one, for the exit of the basi-vertebral veins from the body of the vertebra.

Pedicles (radices arci vertebrae) — The pedicles are two short, thick processes, which project backward, one on either side, from the upper part of the body, at the junction of its posterior and lateral surfaces. The concavities above and below the pedicles are named the vertebral notches; and when the vertebrae are articulated, the notches of each contiguous pair of bones form the intervertebral foramina, already referred to.
Laminæ.—The laminæ are two broad plates directed backward and medialward from the pedicles. They fuse in the middle line posteriorly, and so complete the posterior boundary of the vertebral foramen. Their upper borders and the lower parts of their anterior surfaces are rough for the attachment of the ligamenta flava.

Processes.—Spinous Process (processus spinosus) — The spinous process is directed backward and downward from the junction of the laminæ, and serves for the attachment of muscles and ligaments.

Articular Processes — The articular processes, two superior and two inferior, spring from the junctions of the pedicles and laminæ. The superior project upward, and their articular surfaces are directed more or less backward; the inferior project downward, and their surfaces look more or less forward. The articular surfaces are coated with hyaline cartilage.

Transverse Processes (processus transversi) — The transverse processes, two in number, project one at either side from the point where the lamina joins the pedicle, between the superior and inferior articular processes. They serve for the attachment of muscles and ligaments.

Structure of a Vertebra (Figure 6) — The body is composed of cancellous tissue, covered by a thin coating of compact bone; the latter is perforated by
numerous orifices, some of large size for the passage of vessels; the interior of the bone is traversed by one or two large canals, for the reception of veins, which converge toward a single large, irregular aperture, or several small apertures, at the posterior part of the body. The thin bony lamellae of the cancellous tissue are more pronounced in lines perpendicular to the upper and lower surfaces and are developed in response to greater pressure in this direction (Figure 6). The arch and processes projecting from it have thick coverings of compact tissue.

The Thoracic Vertebrae (Vertebrae Thoracales).

The thoracic vertebrae (Figure 7) are intermediate in size between those of the cervical and lumbar regions; they increase in size from above downward,
the upper vertebrae being much smaller than those in the lower part of the region. They are distinguished by the presence of facets on the sides of the bodies for articulation with the heads of the ribs, and facets on the transverse processes of all, except the eleventh and twelfth, for articulation with the tubercles of the ribs.

Figure 7: A thoracic vertebra.

The bodies in the middle of the thoracic region are heart-shaped, and as broad in the antero-posterior as in the transverse direction. At the ends of the thoracic region they resemble respectively those of the cervical and lumbar vertebrae. They are slightly thicker behind than in front, flat above and below, convex from side to side in front, deeply concave behind, and slightly constricted laterally and in front. They present, on either side, two costal demi-
facets, one above, near the root of the pedicle, the other below, in front of the inferior vertebral notch; these are covered with cartilage in the fresh state, and, when the vertebrae are articulated with one another, form, with the intervening intervertebral fibrocartilages, oval surfaces for the reception of the heads of the ribs. The pedicles are directed backward and slightly upward, and the inferior vertebral notches are of large size, and deeper than in any other region of the vertebral column. The laminae are broad, thick, and imbricated—that is to say, they overlap those of subjacent vertebrae like tiles on a roof. The vertebral foramen is small, and of a circular form. The spinous process is long, triangular on coronal section, directed obliquely downward, and ends in a tuberculated extremity. These processes overlap from the fifth to the eighth, but are less oblique in direction above and below. The superior articular processes are thin plates of bone projecting upward from the junctions of the pedicles and laminae; their articular facets are practically flat, and are directed backward and a little laterallyward and upward. The inferior articular processes are fused to a considerable extent with the laminae, and project but slightly beyond their lower borders; their facets are directed forward and a little mediallyward and downward. The transverse processes arise from the arch behind the superior articular processes and pedicles; they are thick, strong, and of considerable length, directed obliquely backward and laterallyward, and each ends in a clubbed extremity, on the front of which is a small, concave surface, for articulation with the tubercle of a rib. The first, ninth, tenth, eleventh, and twelfth thoracic vertebrae present certain peculiarities, and must be specially considered (Figure 8).
Figure 8: Peculiar thoracic vertebrae.

The First Thoracic Vertebra has, on either side of the body, an entire articular facet for the head of the first rib, and a demi-facet for the upper half of the head of the second rib. The body is like that of a cervical vertebra, being broad transversely; its upper surface is concave, and lipped on either side. The superior articular surfaces are directed upward and backward; the spinous process is thick, long, and almost horizontal. The transverse processes are long, and the upper vertebral notches are deeper than those of the other thoracic vertebrae.
The Ninth Thoracic Vertebra may have no demi-facets below. In some subjects however, it has two demi-facets on either side; when this occurs the tenth has only demi-facets at the upper part.

The Tenth Thoracic Vertebra has (except in the cases just mentioned) an entire articular facet on either side, which is placed partly on the lateral surface of the pedicle.

In the Eleventh Thoracic Vertebra the body approaches in its form and size to that of the lumbar vertebrae. The articular facets for the heads of the ribs are of large size, and placed chiefly on the pedicles, which are thicker and stronger in this and the next vertebra than in any other part of the thoracic region. The spinous process is short, and nearly horizontal in direction. The transverse processes are very short, tuberculated at their extremities, and have no articular facets.

The Twelfth Thoracic Vertebra has the same general characteristics as the eleventh, but may be distinguished from it by its inferior articular surfaces being convex and directed lateralward, like those of the lumbar vertebrae; by the general form of the body, laminae, and spinous process, in which it resembles the lumbar vertebrae; and by each transverse process being subdivided into three elevations, the superior, inferior, and lateral tubercles: the superior and inferior correspond to the mammillary and accessory

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processes of the lumbar vertebrae. Traces of similar elevations are found on the transverse processes of the tenth and eleventh thoracic vertebrae.

![Figure 9: A lumbar vertebra seen from the side.](image)

**The Lumbar Vertebrae (Vertebrae Lumbales).**

The lumbar vertebrae (Figure 9 & 10) are the largest segments of the movable part of the vertebral column, and can be distinguished by the absence of a foramen in the transverse process, and by the absence of facets on the sides of the body.

The body is large, wider from side to side than from before backward, and a little thicker in front than behind. It is flattened or slightly concave above and
below, concave behind, and deeply constricted in front and at the sides. The pedicles are very strong, directed backward from the upper part of the body; consequently, the inferior vertebral notches are of considerable depth. The laminæ are broad, short, and strong; the vertebral foramen is triangular, larger than in the thoracic, but smaller than in the cervical region. The spinous process is thick, broad, and somewhat quadrilateral; it projects backward and ends in a rough, uneven border, thickest below where it is occasionally notched. The superior and inferior articular processes are well-defined, projecting respectively upward and downward from the junctions of pedicles and laminæ. The facets on the superior processes are concave, and look backward and medialward; those on the inferior are convex, and are directed forward and lateralward. The former are wider apart than the latter, since in the articulated column the inferior articular processes are embraced by the superior processes of the subjacent vertebra. The transverse processes are long, slender, and horizontal in the upper three lumbar vertebrae; they incline a little upward in the lower two. In the upper three vertebrae they arise from the junctions of the pedicles and laminæ, but in the lower two they are set farther forward and spring from the pedicles and posterior parts of the bodies. They are situated in front of the articular processes instead of behind them as in the thoracic vertebrae, and are homologous with the ribs. Of the three tubercles noticed in connection with the transverse processes of the lower thoracic vertebrae, the superior one is connected in the lumbar region with the back part of the superior articular process, and is named the
mammillary process; the inferior is situated at the back part of the base of the transverse process, and is called the accessory process (Figure 10)

Figure 10: A lumbar vertebra from above and behind.

Figure 11: Fifth lumbar vertebra, from above.
The Fifth Lumbar Vertebra (Figure 11) is characterized by its body being much deeper in front than behind, which accords with the prominence of the sacrovertebral articulation; by the smaller size of its spinous process; by the wide interval between the inferior articular processes; and by the thickness of its transverse processes, which spring from the body as well as from the pedicles.

The Sacral and Coccygeal Vertebrae

The sacral and coccygeal vertebrae consist at an early period of life of nine separate segments which are united in the adult, so as to form two bones, five entering into the formation of the sacrum, four into that of the coccyx. Sometimes the coccyx consists of five bones; occasionally the number is reduced to three.

The Sacrum (os sacrum).—The sacrum is a large, triangular bone, situated in the lower part of the vertebral column and at the upper and back part of the pelvic cavity, where it is inserted like a wedge between the two hip bones; its upper part or base articulates with the last lumbar vertebra, its apex with the coccyx. It is curved upon itself and placed very obliquely, its base projecting forward and forming the prominent sacrovertebral angle when articulated with the last lumbar vertebra; its central part is projected backward, so as to give increased capacity to the pelvic cavity.
Pelvic Surface (facies pelvina).—The pelvic surface (Figure 12) is concave from above downward, and slightly so from side to side. Its middle part is crossed by four transverse ridges, the positions of which correspond with the original planes of separation between the five segments of the bone. The portions of bone intervening between the ridges are the bodies of the sacral vertebrae. The body of the first segment is of large size, and in form resembles that of a lumbar vertebra; the succeeding ones diminish from above downward, are flattened from before backward, and curved so as to accommodate themselves to the form of the sacrum, being concave in front, convex behind. At the ends of the ridges are seen the anterior sacral foramina, four in number on either side, somewhat rounded in form, diminishing in size from above downward, and directed lateralward and forward; they give exit to the anterior divisions of the sacral nerves and entrance to the lateral sacral arteries. Lateral to these foramina are the lateral parts of the sacrum, each consisting of five separate segments at an early period of life; in the adult, these are blended with the bodies and with each other. Each lateral part is traversed by four broad, shallow grooves, which lodge the anterior divisions of the sacral nerves, and are separated by prominent ridges of bone which give origin to the Piriformis muscle.

If a sagittal section be made through the center of the sacrum (Figure 16) the bodies are seen to be united at their circumferences by bone, wide intervals being left centrally, which, in the fresh state, are filled by the
intervertebral fibrocartilages. In some bones this union is more complete between the lower than the upper segments.

Figure 12: Sacrum, pelvic surface.

Dorsal Surface (*facies dorsalis*).—The dorsal surface (Figure 13) is convex and narrower than the pelvic. In the middle line it displays a crest, the middle sacral crest, surmounted by three or four tubercles, the rudimentary spinous processes of the upper three or four sacral vertebrae. On either side of the middle sacral crest is a shallow groove, the sacral groove, which gives origin to the Multifidus, the floor of the groove being formed by the united laminæ of the corresponding vertebrae. The laminæ of the fifth sacral vertebra, and sometimes those of the fourth, fail to meet behind, and thus a hiatus or
deficiency occurs in the posterior wall of the sacral canal. On the lateral aspect of the sacral groove is a linear series of tubercles produced by the fusion of the articular processes which together form the indistinct sacral articular crests. The articular processes of the first sacral vertebra are large and oval in shape; their facets are concave from side to side, look backward and mediallyward, and articulate with the facets on the inferior processes of the fifth lumbar vertebra. The tubercles which represent the inferior articular processes of the fifth sacral vertebra are prolonged downward as rounded processes, which are named the sacral cornua, and are connected to the cornua of the coccyx. Lateral to the articular processes are the four posterior sacral foramina; they are smaller in size and less regular in form than the anterior, and transmit the posterior divisions of the sacral nerves. On the lateral side of the posterior sacral foramina is a series of tubercles, which represent the transverse processes of the sacral vertebrae, and form the lateral crests of the sacrum. The transverse tubercles of the first sacral vertebra are large and very distinct; they, together with the transverse tubercles of the second vertebra, give attachment to the horizontal parts of the posterior sacroiliac ligaments; those of the third vertebra give attachment to the oblique fasciculi of the posterior sacroiliac ligaments; and those of the fourth and fifth to the sacrotuberous ligaments.
Lateral Surface.—The lateral surface is broad above, but narrowed into a thin edge below. The upper half presents in front an ear-shaped surface, the auricular surface, covered with cartilage in the fresh state, for articulation with the ilium. Behind it is a rough surface, the sacral tuberosity, on which are three deep and uneven impressions, for the attachment of the posterior sacroiliac ligament. The lower half is thin, and ends in a projection called the inferior lateral angle; medial to this angle is a notch, which is converted into a foramen by the transverse process of the first piece of the coccyx, and transmits the anterior division of the fifth sacral nerve. The thin lower half of the lateral surface gives attachment to the sacrotuberous and sacrospinous ligaments, to some fibers of the Glutæus maximus behind, and to the Coccygeus in front.
Figure 14: Lateral surfaces of sacrum and coccyx.

Figure 15: Base of sacrum.
Base (basis oss. sacri).—The base of the sacrum, which is broad and expanded, is directed upward and forward. In the middle is a large oval articular surface, the upper surface of the body of the first sacral vertebra, which is connected with the under surface of the body of the last lumbar vertebra by an intervertebral fibrocartilage. Behind this is the large triangular orifice of the sacral canal, which is completed by the laminæ and spinous process of the first sacral vertebra. The superior articular processes project from it on either side; they are oval, concave, directed backward and medialward, like the superior articular processes of a lumbar vertebra. They are attached to the body of the first sacral vertebra and to the alæ by short thick pedicles; on the upper surface of each pedicle is a vertebral notch, which forms the lower part of the foramen between the last lumbar and first sacral vertebrae. On either side of the body is a large triangular surface, which supports the Psoas major and the lumbosacral trunk, and in the articulated pelvis is continuous with the iliac fossa. This is called the ala; it is slightly concave from side to side, convex from before backward, and gives attachment to a few of the fibers of the Iliacus. The posterior fourth of the ala represents the transverse process, and its anterior three-fourths the costal process of the first sacral segment.
Figure 16: Median sagittal section of the sacrum.

Figure 17: Coccyx
Apex (apex oss. sacri).—The apex is directed downward, and presents an oval facet for articulation with the coccyx.

Vertebral Canal (canalis sacralis; sacral canal).—The vertebral canal (Figure 16) runs throughout the greater part of the bone; above, it is triangular in form; below, its posterior wall is incomplete, from the non-development of the laminae and spinous processes. It lodges the sacral nerves, and its walls are perforated by the anterior and posterior sacral foramina through which these nerves pass out.

Structure.—The sacrum consists of cancellous tissue enveloped by a thin layer of compact bone.

Articulations.—The sacrum articulates with four bones; the last lumbar vertebra above, the coccyx below, and the hip bone on either side.

Differences in the Sacrum of the Male and Female.—In the female the sacrum is shorter and wider than in the male; the lower half forms a greater angle with the upper; the upper half is nearly straight, the lower half presenting the greatest amount of curvature. The bone is also directed more obliquely backward; this increases the size of the pelvic cavity and renders the sacrovertebral angle more prominent. In the male the curvature is more evenly distributed over the whole length of the bone, and is altogether greater than in the female.
Variations.—The sacrum, in some cases, consists of six pieces; occasionally the number is reduced to four. The bodies of the first and second vertebrae may fail to unite. Sometimes the uppermost transverse tubercles are not joined to the rest of the ala on one or both sides, or the sacral canal may be open throughout a considerable part of its length, in consequence of the imperfect development of the laminæ and spinous processes. The sacrum, also, varies considerably with respect to its degree of curvature.

The Coccyx (os coccygis).—The coccyx (Figure 17) is usually formed of four rudimentary vertebrae; the number may however be increased to five or diminished to three. In each of the first three segments may be traced a rudimentary body and articular and transverse processes; the last piece (sometimes the third) is a mere nodule of bone. All the segments are destitute of pedicles, laminæ, and spinous processes. The first is the largest; it resembles the lowest sacral vertebra, and often exists as a separate piece; the last three diminish in size from above downward, and are usually fused with one another.

Surfaces.—The anterior surface is slightly concave, and marked with three transverse grooves which indicate the junctions of the different segments. It gives attachment to the anterior sacrococcygeal ligament and the Levatores ani, and supports part of the rectum. The posterior surface is convex, marked by transverse grooves similar to those on the anterior surface, and presents on
either side a linear row of tubercles, the rudimentary articular processes of the coccygeal vertebrae. Of these, the superior pair are large, and are called the coccygeal cornua; they project upward, and articulate with the cornua of the sacrum, and on either side complete the foramen for the transmission of the posterior division of the fifth sacral nerve.

Borders.—The lateral borders are thin, and exhibit a series of small eminences, which represent the transverse processes of the coccygeal vertebrae. Of these, the first is the largest; it is flattened from before backward, and often ascends to join the lower part of the thin lateral edge of the sacrum, thus completing the foramen for the transmission of the anterior division of the fifth sacral nerve; the others diminish in size from above downward, and are often wanting. The borders of the coccyx are narrow, and give attachment on either side to the sacrotuberous and sacrospinous ligaments, to the Coccygeus in front of the ligaments, and to the Glutæus maximus behind them.

Base — The base presents an oval surface for articulation with the sacrum.
Apex — The apex is rounded, and has attached to it the tendon of the Sphincter ani externus. It may be bifid, and is sometimes deflected to one or other side.

Ossification of the Vertebral Column.—Each cartilaginous vertebra is ossified from three primary centers (Figure 18) two for the vertebral arch and one for
the body. Ossification of the vertebral arches begins in the upper cervical vertebrae about the seventh or eighth week of fetal life, and gradually extends down the column. The ossific granules first appear in the situations where the transverse processes afterward project, and spread backward to the spinous process forward into the pedicles, and lateralward into the transverse and articular processes. Ossification of the bodies begins about the eighth week in the lower thoracic region, and subsequently extends upward and downward along the column. The center for the body does not give rise to the whole of the body of the adult vertebra, the postero-lateral portions of which are ossified by extensions from the vertebral arch centers. The body of the vertebra during the first few years of life shows, therefore, two synchondroses, neurocentral synchondroses, traversing it along the planes of junction of the three centers (Figure 19). In the thoracic region, the facets for the heads of the ribs lie behind the neurocentral synchondroses and are ossified from the centers for the vertebral arch. At birth the vertebra consists of three pieces, the body and the halves of the vertebral arch. During the first year the halves of the arch unite behind, union taking place first in the lumbar region and then extending upward through the thoracic and cervical regions. About the third year the bodies of the upper cervical vertebrae are joined to the arches on either side; in the lower lumbar vertebrae the union is not completed until the sixth year. Before puberty, no other changes occur, excepting a gradual increase of these primary centers, the upper and under surfaces of the bodies and the ends of the transverse and spinous processes being cartilaginous. About the sixteenth year (Figure 19) five secondary
centers appear, one for the tip of each transverse process, one for the extremity of the spinous process, one for the upper and one for the lower surface of the body (Figure 20) These fuse with the rest of the bone about the age of twenty-five.

Figure 18: Ossification of a vertebra

Figure 19: Development of Vertebra
Figure 20: Development of Vertebral body

Figure 21 - Atlas
Figure 22: Axis.

Figure 23: Lumbar vertebra.
Figure 24: Sacrum at birth

Figure 25: Sacrum at 4 ½ Years
Exceptions to this mode of development occur in the first, second, and seventh cervical vertebrae, and in the lumbar vertebrae.

Atlas.—The atlas is usually ossified from three centers (Figure 21). Of these, one appears in each lateral mass about the seventh week of fetal life, and extends backward; at birth, these portions of bone are separated from one another behind by a narrow interval filled with cartilage. Between the third and fourth years they unite either directly or through the medium of a separate center developed in the cartilage. At birth, the anterior arch consists of cartilage; in this a separate center appears about the end of the first year after birth, and joins the lateral masses from the sixth to the eighth year—the lines of union extending across the anterior portions of the superior articular
facets. Occasionally there is no separate center, the anterior arch being formed by the forward extension and ultimate junction of the two lateral masses; sometimes this arch is ossified from two centers, one on either side of the middle line.

Epistropheus or Axis.—The axis is ossified from five primary and two secondary centers (Figure 22). The body and vertebral arch are ossified in the same manner as the corresponding parts in the other vertebrae, viz., one center for the body, and two for the vertebral arch. The centers for the arch appear about the seventh or eighth week of fetal life, that for the body about the fourth or fifth month. The dens or odontoid process consists originally of a continuation upward of the cartilaginous mass, in which the lower part of the body is formed. About the sixth month of fetal life, two centers make their appearance in the base of this process: they are placed laterally, and join before birth to form a conical bilobed mass deeply cleft above; the interval between the sides of the cleft and the summit of the process is formed by a wedge-shaped piece of cartilage. The base of the process is separated from the body by a cartilaginous disk, which gradually becomes ossified at its circumference, but remains cartilaginous in its center until advanced age. In this cartilage, rudiments of the lower epiphysial lamella of the atlas and the upper epiphysial lamella of the axis may sometimes be found. The apex of the odontoid process has a separate center which appears in the second and joins about the twelfth year; this is the upper epiphysial lamella of the atlas. In
addition to these there is a secondary center for a thin epiphysial plate on the under surface of the body of the bone.

The Seventh Cervical Vertebra — The anterior or costal part of the transverse process of this vertebra is sometimes ossified from a separate center which appears about the sixth month of fetal life, and joins the body and posterior part of the transverse process between the fifth and sixth years. Occasionally the costal part persists as a separate piece, and, becoming lengthened lateralward and forward, constitutes what is known as a cervical rib. Separate ossific centers have also been found in the costal processes of the fourth, fifth, and sixth cervical vertebrae.

Lumbar Vertebrae.—The lumbar vertebrae (Figure 23) have each two additional centers, for the mammillary processes. The transverse process of the first lumbar is sometimes developed as a separate piece, which may remain permanently ununited with the rest of the bone, thus forming a lumbar rib—a peculiarity, however, rarely met with.
Sacrum (Figure 24 to 27)—The body of each sacral vertebra is ossified from a primary center and two epiphysial plates, one for its upper and another for its under surface, while each vertebral arch is ossified from two centers. The anterior portions of the lateral parts have six additional centers, two for each of the first three vertebrae; these represent the costal elements, and make their appearance above and lateral to the anterior sacral foramina (Figure 24, 25). On each lateral surface two epiphysial plates are developed (Figure 26, 27) one for the auricular surface, and another for the remaining part of the thin lateral edge of the bone. 17

PERIODS OF OSSIFICATION — About the eighth or ninth week of fetal life, ossification of the central part of the body of the first sacral vertebra commences, and is rapidly followed by deposit of ossific matter in the second and third; ossification does not commence in the bodies of the lower two
segments until between the fifth and eighth months of fetal life. Between the sixth and eighth months ossification of the vertebral arches takes place; and about the same time the costal centers for the lateral parts make their appearance. The junctions of the vertebral arches with the bodies take place in the lower vertebrae as early as the second year, but are not effected in the uppermost until the fifth or sixth year. About the sixteenth year the epiphysial plates for the upper and under surfaces of the bodies are formed; and between the eighteenth and twentieth years, those for the lateral surfaces make their appearance. The bodies of the sacral vertebrae are, during early life, separated from each other by intervertebral fibrocartilages, but about the eighteenth year the two lowest segments become united by bone, and the process of bony union gradually extends upward, with the result that between the twenty-fifth and thirtieth years of life all the segments are united. On examining a sagittal section of the sacrum, the situations of the intervertebral fibrocartilages are indicated by a series of oval cavities (Figure 16).

Coccyx — The coccyx is ossified from four centers, one for each segment. The ossific nuclei make their appearance in the following order: in the first segment between the first and fourth years; in the second between the fifth and tenth years; in the third between the tenth and fifteenth years; in the fourth between the fourteenth and twentieth years. As age advances, the segments unite with one another, the union between the first and second segments being frequently delayed until after the age of twenty-five or thirty.
At a late period of life, especially in females, the coccyx often fuses with the sacrum.

Note 1. A vertebra is occasionally found in which the body consists of two lateral portions—a condition which proves that the body is sometimes ossified from two primary centers, one on either side of the middle line.

Note 2. The ends of the spinous processes of the upper three sacral vertebrae are sometimes developed from separate epiphyses, and Fawcett (Anatomischer Anzeiger, 1907, Band xxx) states that a number of epiphysial nodules may be seen in the sacrum at the age of eighteen years. These are distributed as follows: One for each of the mammillary processes of the first sacral vertebra; twelve—six on either side—in connection with the costal elements (two each for the first and second and one each for the third and fourth) and eight for the transverse processes—four on either side—one each for the first, third, fourth, and fifth. He is further of opinion that the lower part of each lateral surface of the sacrum is formed by the extension and union of the third and fourth "costal" and fourth and fifth "transverse" epiphyses.

The Vertebral Column as a Whole

The vertebral column is situated in the median line, as the posterior part of the trunk; its average length in the male is about 71 cm. Of this length the cervical part measures 12.5 cm., the thoracic about 28 cm., the lumbar 18 cm., and
the sacrum and coccyx 12.5 cm. The female column is about 61 cm. in length.

Curves.—Viewed laterally (Figure 28) the vertebral column presents several curves, which correspond to the different regions of the column, and are called cervical, thoracic, lumbar, and pelvic. The cervical curve, convex forward, begins at the apex of the odontoid process, and ends at the middle of the second thoracic vertebra; it is the least marked of all the curves. The thoracic curve, concave forward, begins at the middle of the second and ends at the middle of the twelfth thoracic vertebra. Its most prominent point behind corresponds to the spinous process of the seventh thoracic vertebra. The lumbar curve is more marked in the female than in the male; it begins at the middle of the last thoracic vertebra, and ends at the sacrovertebral angle. It is convex anteriorly, the convexity of the lower three vertebrae being much greater than that of the upper two. The pelvic curve begins at the sacrovertebral articulation, and ends at the point of the coccyx; its concavity is directed downward and forward. The thoracic and pelvic curves are termed primary curves, because they alone are present during fetal life. The cervical and lumbar curves are compensatory or secondary, and are developed after birth, the former when the child is able to hold up its head (at three or four months), and to sit upright (at nine months), the latter at twelve or eighteen months, when the child begins to walk.
The vertebral column has also a slight lateral curvature, the convexity of which is directed toward the right side. This may be produced by muscular action, most persons using the right arm in preference to the left, especially in making long-continued efforts, when the body is curved to the right side. In support of this explanation it has been found that in one or two individuals who were left-handed, the convexity was to the left side. By others this curvature is regarded as being produced by the aortic arch and upper part of the descending thoracic aorta—a view which is supported by the fact that in cases where the viscera are transposed and the aorta is on the right side, the convexity of the curve is directed to the left side.

Surfaces.—Anterior Surface.—When viewed from in front, the width of the bodies of the vertebrae is seen to increase from the second cervical to the first thoracic; there is then a slight diminution in the next three vertebrae; below this there is again a gradual and progressive increase in width as low as the sacrovertebral angle. From this point there is a rapid diminution, to the apex of the coccyx.

Posterior Surface.—The posterior surface of the vertebral column presents in the median line the spinous processes. In the cervical region (with the exception of the second and seventh vertebrae) these are short and horizontal, with bifid extremities. In the upper part of the thoracic region they are directed obliquely downward; in the middle they are almost vertical, and in the lower part they are nearly horizontal. In the lumbar region they are
nearly horizontal. The spinous processes are separated by considerable intervals in the lumbar region, by narrower intervals in the neck, and are closely approximated in the middle of the thoracic region. Occasionally one of these processes deviates a little from the median line—a fact to be remembered in practice, as irregularities of this sort are attendant also on fractures or displacements of the vertebral column. On either side of the spinous processes is the vertebral groove formed by the laminae in the cervical and lumbar regions, where it is shallow, and by the laminae and transverse processes in the thoracic region, where it is deep and broad; these grooves lodge the deep muscles of the back. Lateral to the vertebral grooves are the articular processes, and still more laterally the transverse processes. In the thoracic region, the transverse processes stand backward, on a plane considerably behind that of the same processes in the cervical and lumbar regions. In the cervical region, the transverse processes are placed in front of the articular processes, lateral to the pedicles and between the intervertebral foramina. In the thoracic region they are posterior to the pedicles, intervertebral foramina, and articular processes. In the lumbar region they are in front of the articular processes, but behind the intervertebral foramina.

Lateral Surfaces.—The lateral surfaces are separated from the posterior surface by the articular processes in the cervical and lumbar regions, and by the transverse processes in the thoracic region. They present, in front, the sides of the bodies of the vertebrae, marked in the thoracic region by the facets for articulation with the heads of the ribs. More posteriorly are the intervertebral
foramina, formed by the juxtaposition of the vertebral notches, oval in shape, smallest in the cervical and upper part of the thoracic regions, and gradually increasing in size to the last lumbar. They transmit the spinal nerves and are situated between the transverse processes in the cervical region, and in front of them in the thoracic and lumbar regions.

Figure 28: Lateral view of the vertebral column.

Vertebral Canal.—The vertebral canal follows the different curves of the column; it is large and triangular in those parts of the column which enjoy the
greatest freedom of movement, viz., the cervical and lumbar regions; and is small and rounded in the thoracic region, where motion is more limited.

Abnormalities — Occasionally the coalescence of the laminae is not completed, and consequently a cleft is left in the arches of the vertebrae, through which a protrusion of the spinal membranes (dura mater and arachnoid), and generally of the medulla spinalis itself, takes place, constituting the malformation known as spina bifida. This condition is most common in the lumbosacral region, but it may occur in the thoracic or cervical region, or the arches throughout the whole length of the canal may remain incomplete.

**Complexity of the thoracic spine pedicle anatomy.**

Transpedicular screw fixation provides rigid stabilization of the thoracolumbar spine. For accurate insertion of screws into the pedicles and to avoid pedicle cortex perforations, more precise knowledge of the anatomy of the pedicles is necessary. This study was designed to visualize graphically the surface anatomy and internal architecture of the pedicles of the thoracic spine. Fifteen vertebrae distributed equally among the upper, middle, and lower thoracic regions were used. For the purpose of mapping surface anatomy, each pedicle was cleaned, spray-painted white, and marked with more than 100 fine points. Using an optoelectronic digitizer, three-dimensional coordinates of the marked points and three additional points, representing a
coordinate system, were digitized. A solid modeling computer program was used to create three-dimensional surface images of the pedicle. To obtain cross-sectional information, each pedicle was sectioned with a thin diamond-blade saw to obtain four slices, 1 mm in thickness and 0.5 mm apart. The pedicle slices were X-rayed and projected onto a digitizer. The internal and external contours were digitized and converted into graphs by a computer. The pedicles exhibited significant variability in their shape and orientation, not only from region to region within the thoracic spine, but also within the same region and even within the same pedicle. These variations are extremely significant in light of current techniques utilized in transpedicular screw fixation in the thoracic spine. Information documenting the three-dimensional complexity of pedicle anatomy should be valuable for surgeons and investigators interested in spinal instrumentation.

1.5 APPLIED ANATOMY OF VERTEBRAE AND PEDICLE

The spinal column (or vertebral column) extends from the skull to the pelvis and is made up of 33 individual bones termed vertebrae. The vertebrae are stacked on top of each other grouped into four regions.
The cervical spine is further divided into two parts; the upper cervical region (C1 and C2), and the lower cervical region (C3 through C7). C1 is termed the Atlas and C2 the Axis. The Occiput (CO), also known as the Occipital Bone, is a flat bone that forms the back of the head.

<table>
<thead>
<tr>
<th>Term</th>
<th>No. of Vertebrae</th>
<th>Body Area</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cervical</td>
<td>7</td>
<td>Neck</td>
<td>C1-C7</td>
</tr>
<tr>
<td>Thoracic</td>
<td>12</td>
<td>Chest</td>
<td>T1 – T12</td>
</tr>
<tr>
<td>Lumbar</td>
<td>5 or 6</td>
<td>Low Back</td>
<td>L1 – L5</td>
</tr>
<tr>
<td>Sacrum</td>
<td>5 (fused)</td>
<td>Pelvis</td>
<td>S1 – S5</td>
</tr>
<tr>
<td>Coccyx</td>
<td>3</td>
<td>Tail bone</td>
<td>None</td>
</tr>
</tbody>
</table>

Table No.1: Different Spinal Levels
Atlas (C1)

The Atlas is the first cervical vertebra and therefore abbreviated C1. This vertebra supports the skull. Its appearance is different from the other vertebrae. The atlas is a ring of bone made up of two lateral masses joined at the front and back by the anterior arch and the posterior arch.

![Atlas & Axis](image)

Axis (C2)

The Axis is the second cervical vertebra or C2. It is a blunt tooth-like process that projects upward. It is also referred to as the 'dens' (Latin for 'tooth') or odontoid process. The dens provides a type of pivot and collar allowing the head and atlas to rotate around the dens.
1.6 THORACIC VERTEBRAE (T1 - T12)

The thoracic vertebrae increase in size from T1 through T12. They are characterized by small pedicles, long spinous processes, and relatively large intervertebral foramen (neural passageways), which result in less incidence of nerve compression.

Figure 31: Thoracic Vertebra
The rib cage is joined to the thoracic vertebrae. At T11 and T12, the ribs do not attach and are called "floating ribs." The thoracic spine's range of motion is limited due to the many rib/vertebrae connections and the long spinous processes.

1.7 LUMBAR VERTEBRAE (L1- L5)

The lumbar vertebrae graduate in size from L1 through L5. These vertebrae bear much of the body's weight and related biomechanical stress. The pedicles are longer and wider than those in the thoracic spine. The spinous processes are horizontal and more squared in shape. The intervertebral foramen (neural passageways) are relatively large but nerve root compression is more common than in the thoracic spine.

![Lumbar Vertebrae](image)

Figure 32: Lumbar Vertebra
1.8 FUNCTION OF THE VERTEBRAE

Although vertebrae range in size; cervical the smallest, lumbar the largest, vertebral bodies are the weight bearing structures of the spinal column. Upper body weight is distributed through the spine to the sacrum and pelvis. The natural curves in the spine, kyphotic and lordotic, provide resistance and elasticity in distributing body weight and axial loads sustained during movement. The vertebrae are composed of many elements that are critical to the overall function of the spine, which include the intervertebral discs and facet joints.

1.9 FUNCTIONS OF THE VERTEBRAL OR SPINAL COLUMN INCLUDE:

| Protection                        | • Spinal Cord and Nerve Roots |
|                                  | • Many internal organs        |
| Base for Attachment              | • Ligaments                   |
|                                  | • Tendons                     |
|                                  | • Muscles                     |
| Structural Support               | • Head, shoulders, chest      |
|                                  | • Connects upper and lower body |
|                                  | • Balance and weight distribution |

Table No.2 : Functions of Spinal Column
1.10 PEDICLES (RADICES ARCII VERTEBRRE).

The pedicles are two short, thick processes, which project backward, one on either side, from the upper part of the body, at the junction of its posterior and lateral surfaces. The concavities above and below the pedicles are named the vertebral notches; and when the vertebrae are articulated, the notches of each contiguous pair of bones form the intervertebral foramina, already referred to. The pedicle is the strongest part of the vertebrae (about 80% of hold of pedicular screw is contributed by the pedicle). It is a tubular structure with an outer cortical shell and central cancellous portion. The dimensions and shape vary between the level of vertebrae.

1.11 TIMELINE OF PEDICLE SCREW

Hadra, first used silver-wire internal fixation for the treatment of a cervical fracture-dislocation and tuberculous spondylitis in 1891. Later, King introduced facet screws for the treatment of degenerative lumbar conditions. Although Boucher has been widely credited with the first use of pedicle screws in North America his report suggests that his innovation was a longer facet screw that occasionally obtained oblique purchase across the pedicle. His screws were not aimed 'down the long axis of the pedicle. Thus, it seems that Harrington and Tullos deserve credit for the first deliberate attempt to put pedicle screws through the isthmus 'of the pedicle.'. Their report, published in 1969, described
the attempted reduction of two cases of high-grade spondylolisthesis. Pioneering the use of pedicle-screw internal fixation proceeded in France and Switzerland during the 1970s. Clinical success with the screws was reported during the 1980s by investigators including Cotrel and Dubousset, Dick, Roy-Camille et al. and Louis. A strong stimulus to North American use of the pedicle-screw technique was the presentation by Roy-Camille at the 1979 American Academy of Orthopaedic Surgeons meeting in San Francisco. Subsequently, a number of American surgeons began to use pedicle screws in the United States. Arthur Steffee used them most creatively. Steffee et al. developed the variable screw-placement (VSP) plate, which permitted pedicle screws to be placed according to individual patient anatomy. This device provided much more clinical latitude than the Roy-Camille plate which had fixed screw-hole distances for application of the screws.

Figure 33: VSP Plate & Screw
Recognizing the clinical utility of pedicle-screw fixation, the North American Spine Society and the Scoliosis Research Society collaborated on a series of introductory meetings to educate spinal surgeons about this new technique. The first of these meetings was held in 1984. These two societies subsequently mutually sponsored the international Meeting on Advanced Spine Techniques, and this annual meeting continues to be held to the present day. Since the introduction of pedicle screws, engineers, surgeons, radiologists, neurophysiologists, anatomists, epidemiologists, and statisticians have made fundamental efforts to improve what was recognized universally as a clinical liability in surgical spine care: the lack of truly high-quality spinal internal fixation similar to what was available for internal fixation of long bones. The basic and clinical science of pedicle screws developed from their introduction and infancy in the early 1970s to widespread acceptance, as indicated in "State-of-the-Art Treatment" statements by the North American Spine Society in 1993 and 1996, which endorsed the use of pedicle screws by experienced surgeons. Review articles described the evolution of treatment methods as surgical experience accumulated.

1.12 ANATOMY OF PEDICLE

The anatomy of the human pedicle has been studied exhaustively in different races in children and in adults. Patterns of pedicle anatomy unique to the cervical spine the thoracic and the lumbar spine and the sacrum have been
clearly identified. Measurements of the outer and inner diameters of the pedicle have been performed extensively. The inner diameter of the pedicle - the critical surgical dimension - has been shown to be more directly related to the height of the patient than to the gender. However, wide individual variations within common patterns of anatomy are the rule. This forces the surgeon to understand the individual anatomy of the patient, in order to achieve clinical success, and to appreciate the patterns of pedicle anatomy that are common to the human race in general. There do not seem to be more than modest differences in pedicle anatomy from race to race.

Several investigators have studied the morphology of the thoracic pedicle and its relation to adjacent vital structures. Berry et al, Panjabi et al, Scoles, Zindrick et al, Vaccaro et al, and Ebraheim et al have reported detailed anatomic data of the thoracic pedicle, including dimensions and angulations. Also, the internal structure of the thoracic pedicle has been documented quantitatively. To aid in accurate placement of a screw into the pedicle, Rou et at, Vaccaro et al, and Ebraheim et al defined the entrance point for screw insertion on the posterior aspect of the thoracic spine. Furthermore, Weinstein et al and Ebraheim et al described the anatomic relation of the thoracic pedicle to the adjacent neural structures.
A thorough knowledge of the anatomy of the pedicles is necessary for the use of pedicle fixation. The pedicle connects the posterior elements to the vertebral body. Medial to the pedicle are the epidural space, nerve root, and dural sac. The exiting nerve root at the level of the pedicle is close to the medial and caudal cortex of the pedicle. (Figure 34)

Figure 34: Errors in pedicle screw placement
A. Nerve root impingement by screw violating medial pedicle wall.
B. Pedicle screw out inferiorly. (From Pinto MR: Spine: State of the Art Reviews 6:45. 1992.) Close to the lateral and superior aspects of the pedicle cortex is the nerve root from the level above. At the L3 and L4 vertebral bodies the common iliac artery and veins lie directly anterior to the pedicles (Figure 35).
Figure 35 Vascular damage by insertion of screw beyond anterior cortex. (from Pinto MR: Spine: State of the Art Reviews 6:45, 1992)

Figure 35: Vascular Damage

In the sacral region the great vessels and their branches lie laterally along the sacral ala. In the midline of the sacrum a variable middle sacral artery can lie directly anterior to the S1 vertebral body. Anterior penetration of a vertebral body can occur without being apparent on roentgenogram unless a "near approach" view is obtained (Figure 36).

Figure 36: Relevance of "Near Approach View"

Figure 31 "Near approach" roentgenographic view to decrease likelihood of
anterior screw penetration. When drill (or screw or probe) tip is actually at anterior cortex, lateral view (0 degrees) misleadingly shows tip still to be some distance (A) away from cortex. At too oblique an angle of view (60 degrees), tip appears to be some distance (B) from cortex. Only when view is tangent to point of penetration (30 degrees in this illustration) does tip appear most nearly to approach actual breakthrough. (From Krag MH: Spine 16:84, 1991.)

Zindrick et al. studied the size of pedicles in mature and immature spines. They found that the transverse pedicle width at the 15 and 14 levels reached 8 mm or more in children 6 to 8 years of age, but transverse width at 13 approaching 8 mm was not seen until 9 to 11 years of age (Figure 37).

![Figure 37 - Transverse pedicle isthmus width. (From Zindrick Mr. Wiltse LL, Doornik A, et al : spine 12:160, 1987).](image)

The distance to the anterior cortex increased dramatically from the youngest age group until adulthood at all levels (Figure 38).
Figure 38 - Distance to anterior cortex through pedicle angle axis versus through line parallel to midline axis of vertebra. (From Zindrick MR, Wiltse LL, Doornik A. et al: Spine 12:160, 1987.)
References:


