



M. ROTH

HOMINIZATION OF THE SKELETON: A NEUROCRANIAL, NEUROSPINAL AND OSTEONEURAL DEVELOPMENTAL PROCESS

ABSTRACT — The notion is advocated and supported by gross morphological argumentation that the neuro-cranial developmental relation, viz., the dependence of the shape of the neurocranial bony envelope upon the size and shape of the growing brain does not represent but the most striking local manifestation of the universal osteoneural relation between the developing bony and nervous tissue in general, i.e. in the axial organ, in the limbs as well as in the facial area. The gross anatomical features of the skeleton, above all those associated with hominization appear to have been evolved as adaptations to the growth peculiarities of the respective nervous structures.

KEY WORDS: Hominization — Spinal cord — Vertebral column — Limb bones — Facial skeleton — Neural growth.

INTRODUCTION

With the emergence of the tetrapods in the Devonian and Carboniferous, the vertebral column assumed new functions and was subjected to many stresses and strains which were not present in a completely aquatic environment. Although the primary function of the vertebral column was still protection of the spinal cord, it now also served as a sort of beam supporting the weight of the head, ribs, viscera, etc., which has formerly been carried by the water (Rockwell et al., 1938). The former function of the spine, implying dependence of its shape upon the morphology of the encased neural content, has been entirely forgotten by osteology in connection with the overwhelming study of biomechanics, viz., of the latter function of the vertebral column alone.

The dependence of the shape of the neurocranium upon the shape and size of the growing brain has been since ever recognized. This simple developmental relation is an important source of information about the brain morphology of extinct vertebrates including ancestors of man. The brain is looked upon in this

connection as a lump of growing nervous tissue the intricate functions of which such as the motoric, sensoric, vegetative or associative are entirely disregarded since irrelevant for explanation of the neurocranial shape. Concerning the spinal and peripheral nervous system the very opposite approach is adopted, viz., their functions are almost exclusively taken into account whereas the spinal and peripheral neural growth is either disregarded or held for a passive process which just follows the outgrowth of the other tissues, above all of bones. The developmental history of the vertebral column is linked with the well-studied early embryonic events including the installation of the mesoderm, the somites, sclerotomes, notochord etc. with gradual chondrification and ossification of the outgrowing axial structure. In quite isolated instances the relation of the vertebral primordium to the embryonic spinal cord was taken into consideration (Holtzer, 1952; Watterson et al., 1954 a.o.). The postembryonic development of the vertebral column is considered and studied, however, as entirely independent upon its neural content. It is the intention of the present author to cover the gap in knowledge

resulting from that approach and to show that adherence to the same morphogenetic principles like those exemplified in the neurocranium, viz., to the notion of actively growing spinal nervous structures encased secondarily by the axial skeleton should be helpful in better understanding a number of normal and pathological features of the spine. This approach does not necessitate to search for any new facts concerning the spine or its neural content. It would seem enough to bear in mind that the two basic components of the axial organ, treated in anatomical handbooks in widely separated chapters, "belong together" as does the brain and its skeletogenic envelope.

Moreover, an attempt has been undertaken recently (Roth 1971, 1982, 1985) to extend the principles of the neurocranial and neurospinal developmental relation to the appendicular and facial skeleton as well, viz., to interpret the neurocranial relation just as a local and most striking manifestation of an universal osteoneural relation between the developing nervous and bony macrostructures throughout the vertebrate body. In the present communication, specific anthropological aspects of that concept will be dealt with, above all the osteoneural mechanism of hominization of the skeleton.

THE RELATIVE NEUROVERTEBRAL GROWTH

In 1919, Streeter published his classic diagram of the ascent of the spinal cord in man (Fig. 1). In four subsequent developmental stages reproduced in the same relative size, the lower end of the primordial spinal cord is seen to rise cranially in respect to the embryonic vertebral column. In the presented form the diagram is somewhat misleading since it prompts the reader to conceive the spinal cord as an entirely isolated structure just "ascending" within the spine, without any further developmental relation to it. Even the "ascending" cord remains, however, in the most intimate developmental relation with the growing spine by mediation of the huge mass of about 30 pairs of spinal nerve roots, left and right, ventral and dorsal, which run like reins around the pedicles of the individual vertebrae (Fig. 2B; 3d, e; 5). Any growth dissociation of the cord and spine is out of question. In the present context it appears convenient to consider the spinal cord with the nerve roots as a whole, the "cord-nerve roots-complex" (CNRC).

Moreover, Streeter's diagram does not reflect adequately the growth dynamics of the axial organ which in vertebrates including man elongates distally with the spinal cord lagging more or less behind (Fig. 2A). In the adult man the lower end of the cord is situated at the level of L1-2, in quadrupeds such as the dog, rabbit or rat much lower, at the level of the lumbo-sacral junction area; a distinct degree of the ascent is present, however, even in these animals (Fig. 3d; 5A-b). The law of cranio-caudal developmental direction, entirely disregarded in human biology, is dramatically documented by the downward slant of the spinal nerve roots and by formation of the

cauda equina (Fig. 2B). The seemingly upwards directed gain in height of a growing child is nothing but an optical illusion. The cranio-caudal direction of growth of the axial organ thus parallels the proximodistal developmental direction of the limbs.

Not unlike the neurocranium, the axial skeleton represents a bony envelope reflecting the gross anatomical features of the enclosed neural contents, both in the transversal and in the longitudinal direction. The latter point should be especially emphasized since the spinal nerve roots are believed to be "taken in tow" and dragged along by the distally growing vertebral column, as though the degree of longitudinal outgrowth of the nerve roots would be determined by the degree of growth in length of the vertebral column. Actually, however, the CNRC represents together with the brain an actively growing nervous structure which determines the shape of its bony envelope. Length and width of the vertebrae depend upon the (phylo)genetically established growth-in-length potentiality of the CNRC, i.e. upon the various amount of space available for the growing vertebrae along the neural content (Fig. 3d, e). Accordingly, in quadrupeds (with the number of vertebrae at least approximately comparable with that of man) the vertebrae grow up longer and slender whereas the comparatively shorter CNRC in man is associated with shorter and broader (brachyspondylic) vertebrae (Fig. 5A, B; 6A, B; 7a-f).

One is thus led to the conclusion that the vertebral shape is not rooted in any intrinsic "genetic" potentiality of the vertebral bone tissue proper but rather in the (phylo)genetics of the spinal neural growth. The developing vertebrae are simply "carried with" the CNRC growing more or less in length and providing in this way for the appropriate vertebral shape. The bone growth, rather than the neural growth, displays passive properties in the course of development. The primordia of the brain, spinal cord and of the spinal ganglia become embedded by the enveloping skeletogenic tissue as though by lava (Töndury 1958).

HOLTZER'S NEUROPROTECTIVE MECHANISM

The accumulating cranial and axial skeletogenic tissue maintains very stubbornly a distinct "respectful" distance from the surface of the enclosed neural contents (Fig. 8a, b). This phenomenon shown by Holtzer (1952) in amphibian embryos but common to all vertebrates as an universal neurobiological property, points to something like a morphogenetic field around the nervous structure probably maintained by some metabolic product released from the neural surface to which precartilaginous cells react in a negative chemotaxic fashion (Holtzer 1952). The precartilaginous cells are thus deployed in such a way that a lumen is left in the cartilaginous mass the shape and size of which depends upon the size and shape of the enclosed nervous bundle. Baumann (1951) speaks in this connection about a "victory" of the nervous tissue over the cartilage.

The appearance of the subarachnoid space filled with cerebrospinal fluid in the early embryo fairly simultaneously with the first signs of chondrification, i.e. with a distinct stiffening of the primordial skeletogenic envelope, appears to fulfil, among other functions, the role of Holtzer's neuroprotective mechanism. In this way, as an active "instinct of self-preservation" of its own, the nervous substance defends its organ integrity and, at the same time, determines the gross shape of the neurocranial and neurospinal bony envelope.

QUANTITATIVE NEUROVERTEBRAL DEVELOPMENTAL SHIFT

To understand the dynamics of the neurovertebral growth relations necessitates to take into account the profound quantitative shift which takes place in the course of development between the nervous and the bony vertebral tissue and which is most markedly reflected in the shape and size of the vertebral and intervertebral foramina (Fig. 8a-d; 9a-c). Concerning the former, the comparatively enormous embryonic spinal cord is only partly covered by the vertebral body anlage while the neurapophyses diverge widely to embrace at least partially the massive cord. In the course of subsequent development, however, the neurapophyses gradually close to form a complete vertebral arch around the relatively diminishing cross-section of the spinal cord. The same is true as concerns the comparatively huge embryonic spinal ganglia within the correspondingly ample primordial intervertebral foramina the size of which in the lumbar region, for instance, exceeds the size of the primordial vertebral bodies (Fig. 6A-a). The relative size of the spinal ganglia decreases steadily together with the relative volume reduction of the entire central nervous system. The bulk of the skeletogenic envelope, on the other hand, steadily increases. Both processes, the neural decrease and the bony increase, adequately and precisely balanced, are dramatically reflected in the lateral roentgenograms of the lumbar spine (Fig. 6A/a-f). The infantile spine is characterized by large transverse-oval foramina still recalling the embryonic shape so that the vertebral arch is correspondingly thin. With increasing amount of bone tissue the vertebral arches get thicker and cranio-caudally longer, the vertebral bodies larger and the intervertebral (and vertebral) foramina smaller — all these skeletal morphogenetic events dependent upon, and in intimate balance with, the relative size reduction of the enclosed (but invisible in the roentgenogram) nervous components (Fig. 9a-c).

DEVELOPMENTAL GANGLIOFORAMINAL RELATION

There exists just one important difference between the neurocranial and neurospinal development, viz., a distinct lagging behind of the spinal neural growth in respect to that of the vertebral column. The neurovertebral growth differential is manifested in the obliquity of the spinal nerve roots appearing as early

as in the 20 mm (7-week-) human embryo (Fig. 4b), i.e. at least one month before the onset of the ascent, at a time when the spinal cord still occupies the entire length of the spinal canal. The neurovertebral growth differential refers to the CNRC in whole, the ascent is just an episode "grafted" on the already preexisting neurospinal growth differential. In addition to the increasing obliquity of the spinal nerve roots, the differential is manifested by the cranially-eccentric position of the spinal ganglia within their intervertebral foramina. Every ganglion "cuts in" from below into the vertebral arch and in this way — by mediation of Holtzer's neuroprotective mechanism — the caudal vertebral incisura is moulded. This is the reason why intervertebral foramina in man are not circular but "drawn out" cranially (Fig. 6A; 8c-d). Owing to the dorsolateral course of the thoracic spinal nerves within the paravertebral gutter of the thoracic wall (Becker 1940; Kunert 1963; Roth 1969) the thoracic foramina become pear-shaped whereas the lumbar foramina become rather kidney-shaped under the effect of the ventro-laterally coursing lumbar spinal nerves (Fig. 6A; 8; 10a-c). The nerves at the thoraco-lumbar junction leave the spinal canal in a roughly "neutral" lateral direction (Fig. 16b). In accordance with the course of the L4 and especially of the L5 nerve their foramina as well as pedicles are situated more ventrally as compared with the cranial lumbar foramina. The L5 vertebra is thus easily discernible from, say, L3 vertebra according to the more ventrally inserting pedicle in the former (Fig. 10b, c).

In this connection the last thoracic vertebra from *Australopithecus*, *Paranthropus* and *Homo sapiens* illustrated by Robinson (1970) should be alluded to. While in the latter the caudal vertebral incisura extends slightly dorso-cranially, in the two former the incisura is rather vertically-oval, still "quadruped-like", obviously reflecting the lack of a deeper paravertebral groove and, consequently, of a full erect posture in the two ancestors of man. (The difference in the shape of the incisura just mentioned is indicated — in an accentuated form — in the respective inserts in the Fig. 26).

In the quadruped with its comparatively long CNRC the spinal ganglion cuts only slightly into the vertebral arch so that the caudal vertebral incisura is shallower than in man (Fig. 6A-f; 10d). The primordial vertebral pedicle is laid down as a "tongue" of skeletogenic tissue extending from in front into the interganglionic space (Sensenig 1949) (Fig. 6A-a; 8a). Together with the different degree of cranio-caudal growth in length of the CNRC the interganglionic distances get longer in the quadruped than in man and, accordingly, the vertebral arch together with the vertebral body grows up to a greater or lesser length. The spinal ganglia thus appear to represent something like "pacemakers" of the vertebral growth in length.

THE "PACEMAKER" ROLE OF THE SPINAL GANGLIA IN VERTEBRAL GROWTH

The abovementioned role of the spinal ganglia seems to be corroborated by the following roentgen-

anatomical observations. With neuro-adaptive shortening of the vertebrae in the course of hominization the length (i.e. cranio-caudal "thickness") of the intervertebral disc is increased. This means that the intervertebral cartilaginous material was more "spent" in the quadruped by the ossification process than in man. Consequently, the degree of longitudinal extension of the vertebral ossification and the length ("thickness") of the intervertebral disc are indirectly proportional and both neurovertebrally determined, dependent upon the amount of space available along the CNRC, viz., upon the length of the interganglionic distance (Fig. 3d, e; 5B/a—c; 6A/d—f).

To fulfil the role of "pacemaker" the spinal ganglion must be located within the intervertebral foramen, viz., near the lower border of the pedicle. A remarkable exception to that rule are the sacral spinal ganglia which have an extraforaminal location, within the spinal canal (Fig. 11d). Together with the entire vertebral column, the sacrum originates as a skeletogenic envelope of the preformed nervous structures, viz., of the lower end of the spinal cord and of the huge embryonic sacral ganglia that "enforce" — by mediation of Holtzer's mechanism — the establishment of the appropriate cavities and foramina within the growing sacral bony mass. In the early embryo the sacral ganglia are thus situated within the intervertebral foramina (Lebedkin 1936) (Fig. 11a).

In the about 5-month fetus the ganglia have already left, however, the intervertebral foramina, obviously in connection with a purposeful slowing down of growth of the respective nerve roots (Fig. 11b). In the newborn the sacral ganglia begin to "crowd" within the spinal canal at the proximal sacral level indicating the definitive arrangement in the adult (Fig. 11c, d).

It should be borne in mind that the difference in length of the spines reproduced in Fig. 11b and c is, in reality, incomparably greater (fetus — newborn!) so that the sacral nerve roots, in both diagrams of approximately the same length, are in the fetus (b) much shorter than in the newborn (c).

In the light of the adduced evidence, the extraforaminal location of the sacral ganglia should mean "de-curbing" of the vertebral ossification process resulting in physiological fusion of the sacral vertebrae with preservation of a very thin residual intervertebral disc (Fig. 11e), viz., in an exaggerated degree of what happens in quadrupeds as compared with man. "De-curbing" of the ossification process in the quadruped resulting in a much thinner intervertebral disc than in man is related, however, to the lesser curbing effect of the long CNRC and long interganglionic distance, not to extraforaminal location of the ganglia like in the sacrum. The effect upon the vertebral morphology is, however, the same or very similar.

It should be noted that physiological fusion of the cervical vertebrae in *Halicore dugong* (Dexler and Eger 1911) and most likely in other sea mammals is associated with intraspinal, extraforaminal location of the cervical spinal ganglia as well.

Isolated congenital vertebral block in man, most frequently encountered in the cervical spine, is usually associated with an undersized intervertebral foramen

(Fried 1963; Vyhnanek and Lorencová 1984) Fig. 12a, b). In accordance with the neurovertebral concept and with the observations of Gonzalo-Sanz (1972) the undersized foramen mirrors an undersized, hypoplastic spinal ganglion. Equally, however, it could point to an intraspinal location of the ganglion, viz., to a growth insufficiency of the respective nerve roots with the foramen filled just with the spinal nerve the cross-section of which is smaller than that of the ganglion. Be it as it may, the hypoplastic or extraforaminal pair of ganglia does not "curb" sufficiently the ossification process, the intervertebral cartilage will be more "spent" than usually and a vertebral block ensues with exactly the same general features as that involving normally the sacral vertebrae, above all as concerns the residual disc common to both (Fig. 12a—c; 13a—d).

According to all appearance, "removal" of the spinal ganglia from the intervertebral foramina by means of slowing down the growth of the nerve roots is instrumental in the production of physiological and, as an aberration, of pathological developmental vertebral fusions.

OSTEO-NEURAL "MORPHOGENETIC INERTIA"

The ganglio-foraminal developmental relation appears to reflect the following hitherto ignored neurobiological phenomenon: With the relative diminution of the spinal ganglion in the course of development one would expect, as a matter of fact, rather a correspondingly smaller intervertebral foramen. The latter appears, however, to retain the relative size as determined by the comparatively huge embryonic spinal ganglion (Fig. 6A—a; 8a), despite the distinct reduction in size associated with the neurovertebral developmental quantitative shift. The cranial vertebral incisura thus reflects the caudal contour of the embryonic spinal ganglion (Fig. 8; 10a—d). One feels to be confronted in this special case with what could be termed "osteo-neural morphogenetic inertia" and what is documented in the neuro-cranial development in fishes. Whereas in the fish embryo the brain is tightly enveloped by the skeletogenic case, in the course of postembryonic development the brain growth lags behind that of the neurocranium (Werner 1927; 1958—59; Bronsch 1950). The anterior border of the latter, though moving ahead from the receding frontal border of the slower growing brain, retains the shape originating as an "imprint" of the embryonic brain (Werner 1927). The free space between the small brain and the large bony envelope is filled with liquor or fatty tissue, the optic and olfactory nerves are significantly lengthened (Werner 1927; Bronsch 1950). As a matter of fact, something like "ascent (or better "descent") of the brain at the cranial end of the fish body parallels the ascent of the spinal cord at the caudal end of the mammalian body. In both instances the respective nerves, cranial or lumbosacral, are correspondingly lengthened. An essentially identical process may be traced, in miniature, in the ganglio-foraminal developmental relation.

Topic correlations should be thus searched for in embryos since in the adult forms they can be already lost or obscured (Werner 1958—59). In the given instance of the adult fish, if approached without due regard to the embryonic arrangement, the cranial cavity may be misconceived as being independent upon the growing brain.

NEUROVERTEBRAL GROWTH MECHANISM OF PHYSIOLOGICAL CURVATURES OF THE SPINE

Cranial eccentricity of the spinal ganglion within the intervertebral foramen means that the entire nervous tissue tract from the brain to the level of the respective ganglion has grown a little less in length than the corresponding portion of the vertebral column; the difference amounts in the adult to 10—15 mm (Fig. 8a). When two structures elongate side by side at different rates they become curved. This may be illustrated by means of a bimetallic stripe which may be curved either by extrinsic mechanical force (i.e. by muscular action on the spine) or by heating, i.e. by different rate of elongation of its two components (Fig. 14a, b).

Exactly the same situation exists in the developing axial organ the two main components of which grow side by side at different rates. The hyperkyphotic curve of the early embryo is attributed to the rapid growth of the dorsally situated early primordia of the brain and spinal cord. With the onset of the neurovertebral growth differential the roles become reversed: From now on the spinal nervous structures assume the role of a retarding ("curbing") factor for the ever faster growing vertebral column and this results in gradual straightening of the embryonic body culminating in the production of lumbar lordosis (Fig. 3; 4). The first distinct lumbosacral lordotization (promontory) appears as early as in the 20 mm human embryo simultaneously with the beginning obliquity of the lumbosacral nerve roots (Fig. 4a—c). The promontory should be then looked upon as the first visible effect of the locally enhanced neurovertebral growth differential. The primary curvatures of the spine, viz., thoracic and sacro-coccygeal kyphosis represent remnants of the primordial embryonic hyperkyphosis. Secondary cervical lordosis which appears much earlier than is usually supposed, viz., as early as in the 9,5 mm embryo (Bagnall 1977) should be related to the same neurovertebral growth mechanism like the lumbar curve. In the course of months and years of the developmental period of life the spine as a whole including the sacrum is "thrown in curvatures" along the neural content lagging behind, viz., being somewhat shorter than the spine in every moment of development. In the quadruped with its comparatively longer CNRC the neural "curbing" effect is less pronounced than in man and so is also the lumbosacral lordosis (Fig. 3d; 15a).

The matter may be well illustrated by means of a thin wire introduced into the spinal canal of a fresh rat cadaver and fixed at the foramen magnum (Fig. 15a, b). With shortening of the wire imitating

the primary growth reduction of the CNRC in the course of hominization the slight quadrupedal spinal curvatures become exaggerated including accentuation of the promontorium. It should be noted that the cervical hyperlordosis strikingly resembles that of the living animal in normal posture (Vidal et al., 1986) (Fig. 26 below). Neuro-adaptive shortening and widening of the individual vertebrae associated with hominization cannot be, of course, reproduced in the abovementioned experiment.

The lordotization effect of the neurovertebral growth differential does not involve any mechanical pull of the nerve roots upon the growing spine. A plastic adaptation of the lumbosacral and cervical spine to the retarded growth of the CNRC is involved under mediation of Holtzer's neuroprotective mechanism which provides for a free space between the spinal ganglion and the roof of the intervertebral foramen (Fig. 3; 8a, b) so that the spinal nerve roots, in spite of their retarding effect upon the gross vertebral growth, maintain a slackened, wavy course (Fig. 6B—d). In this way the spinal nerve roots defend their integrity in the longitudinal direction, viz., any deleterious longitudinal stretch of the spinal cord or of the nerve roots is avoided.

The ganglio-foraminal relation is, however, not the same throughout the lumbar spine. The nerves L4 and L5, i.e. those mainly responsible for the lumbar lordosis involving in the first place the L4 and L5 vertebrae, show a much more intimate relation to the lower circumference of the pedicles than the cranial lumbar nerves (Jonck 1961; Kravenbühl and Zander 1955 and any handbook of topographic anatomy) (Fig. 6B—d). This arrangement appears to be related to the accentuated "curbing" effect of the L4,5 nerve roots upon the growing spine reflected in obliquely divergent caudal outline of the L4 and L5 pedicles as compared with that of L1 or L2 (Fig. 5A—d, e). The L4,5 pedicles "spread" more in the transversal direction as a response to the increased neural curbing effect they meet with in the course of distally proceeding growth of the spine. Growth retardation of the lumbosacral nerve roots appears ahead of the other nerve roots in the early embryo (Fig. 4b) and persists through infancy and adolescence until adulthood. The definitive lumbar lordosis appears during the first 3 years after birth (Reichmann and Lewin 1971), i.e. comparatively late in development — a circumstance which might contribute to the more intimate adherence of the L4,5 nerves to the pedicles. Inevitably, the L4,5 nerve roots dispose of a lesser "length reserve" in respect to the vertebral column than the other nerve roots (Fig. 6B—d). It may be anticipated that this local reduction of the length reserve may attain critical levels.

It deserves mention in this context that the reduced length reserve of the L4,5 nerve roots strikingly coincides with the most frequent location of disc "degeneration". The latter is generally attributed to the mechanical strains resulting from erect posture, particularly to the shear component of the vertical compression forces (Thieme 1950 a.o.). The possible causal relation of disc degeneration to the nerve root-ganglio-foraminal relation and its disturbances would deserve further study.

GIRTH OF THE VERTEBRAL BODY

The fact that the vertebral column grows faster in length than its neural content implies that every individual vertebra possesses a distinct surplus of growth potential with respect to the corresponding portion of the CNRC. This proliferative surplus cannot be spent in the longitudinal direction since this is opposed by the curbing effect of the slower growing neural content. The skeletogenic surplus is thus manifested in the transverse direction in the form of a circumferential overgrowth at the cranial and caudal end of the vertebral body where accumulation of the enchondrally proliferating osteogenic material takes place. The onset of this process coincides with the first signs of the neurovertebral growth differential and results in the concavity of the ventral and lateral surfaces of the vertebral body. The vertebrae, so to say, begin to be somewhat "short of space" along the CNRC, they have to accommodate along it by spreading partially in the transversal direction. Streeter's diagram (Fig. 1) shows just the first appearances of that phenomenon which remains lifelong evident in the ventral and lateral concavity of the vertebral body (Fig. 5A, B; 6A, B) — a very purposeful arrangement from the viewpoint of biomechanics of the erect posture. It should be noted, however, that in quadruped's vertebrae the girth concavity is encountered as well (Fig. 6A—f; 15). The dorsal concavity of the vertebral body is much less or absent since its transversal growth takes place only in the ventral and lateral direction but not posteriorly towards the spinal canal with consequent non-encroachment upon its lumen (Knutsson 1961), doubtlessly as a result of the "instinct of self-preservation" of the CNRC.

CROSS-SECTIONAL NEUROVERTEBRAL RELATION

It appears self-evident that the cross-sectional shape of the spinal canal (i.e. the shape of the foramen vertebrae) mirrors that of the spinal cord (Knutsson 1961 a.o.). In the lumbar portion, however, any relation between the nerve roots of the cauda and the shape of the vertebral foramina is not evident at the first sight. To understand that relation one should recall the experiment by Watterson et al. (1954) (Fig. 17): Removal of the spinal cord in the chick embryo results in bony obliteration of the spinal canal. The ascent of the spinal cord in man represents, as a matter of fact, a similar experiment of Nature: The ascending cord is "removed" from the lumbosacral spinal canal the lumen of which remains at first approximately circular as it was moulded originally by the huge embryonic spinal cord (Fig. 18c). The nerve roots distributed along the dorso-lateral wall of the spinal canal (Fig. 18c—e) seem to have hardly anything in common with the shape of the vertebral foramen. Exactly like after the experimental removal of the spinal cord in the chick embryo, however, obliteration of the spinal canal takes place also in man — gradually, in the course of months and years, and not completely since the lumbosacral spinal canal harbours nerve

roots of the cauda disposing of Holtzer's neuroprotective mechanism. At the level of L1 the overall cross section of the cauda is circular and so is also the shape of the vertebral foramen. At the level of L4,5 the mass of the cauda is already diminished so that the vertebral foramina become partially obliterated and assume the shape of a trefoil. The ventro-lateral recesses of the trefoil represent imprints (groovings, carvings) of the massive L4,5 nerves leaving the spinal canal in the ventro-lateral direction (Fig. 16d; 18f; 19; 20). The triangular shape of the cervical vertebral foramina (Fig. 16a) is related to the same neuroprotective effect of the cervical spinal cord together with the ventro-laterally coursing cervical nerve roots. The shallow bilateral recess of the L1 foramen rendering its shape rather transverse-oval (Fig. 16b) is a similar product of the L1 nerve leaving the spinal canal in the lateral ("neutral") direction.

The dorso-lateral distribution of the lumbosacral nerve roots within the spinal canal demonstrated by means of computerized tomography (Pettersson and Harwood-Nash 1982) is due to their slower growth rate as compared with that of the vertebral column, viz., to the mechanism of lordotization. Owing to their lagging behind the nerve roots are crowded in the dorsal portion of the spinal canal where, impinging upon the dorsal wall of the originally circular vertebral foramen, they produce a triangular recess, the dorsal leaf of the trefoil (Fig. 16d; 18f; 20). Not unlike the intervertebral foramina have been drawn-out cranially by the effect of the growth-retarded spinal nerve roots and of the cranial eccentricity of the spinal ganglia, the L4,5 vertebral foramina have been drawn out dorsally by the impinging cauda equina.

In *Australopithecus*, the dorsal recess of the L5 trefoil is much shallower than in recent man (Robinson 1970) reflecting obviously the lack of any appreciable lumbar lordosis in that ancestor of man.

THE MUSCLES AND THE SPINE

The role of musculature in the morphogenesis of the spine is by no means nullified by the proposed concept. The muscles seem to exert, however, just a modificatory effect: The basic, neurovertebrally evolved axial bony structure ("arch-structure") is set in motion by muscles according to the momentary needs of function, locomotion and antigravitation with modifications of the surface relief such as protuberances, processes or crests at the sites of muscle insertions (Fig. 18f; 21). The external occipital protuberance can serve as a crucial example (Fig. 3d, e): It is evidently produced by muscular insertions on the neurocranium the general saucer-like shape of which reflects, however, the shape and size of the enclosed brain. Exactly in the same way the spine, irrespective of all its processes, mirrors the gross anatomical features of the enclosed CNRC, both in the transversal and in the longitudinal direction. On the spine flanked with the bulky muscles the insertional bony prominences and processes are much more prominent than those on the human neurocranium. With the greater mass of muscles inserting upon the latter in various man-

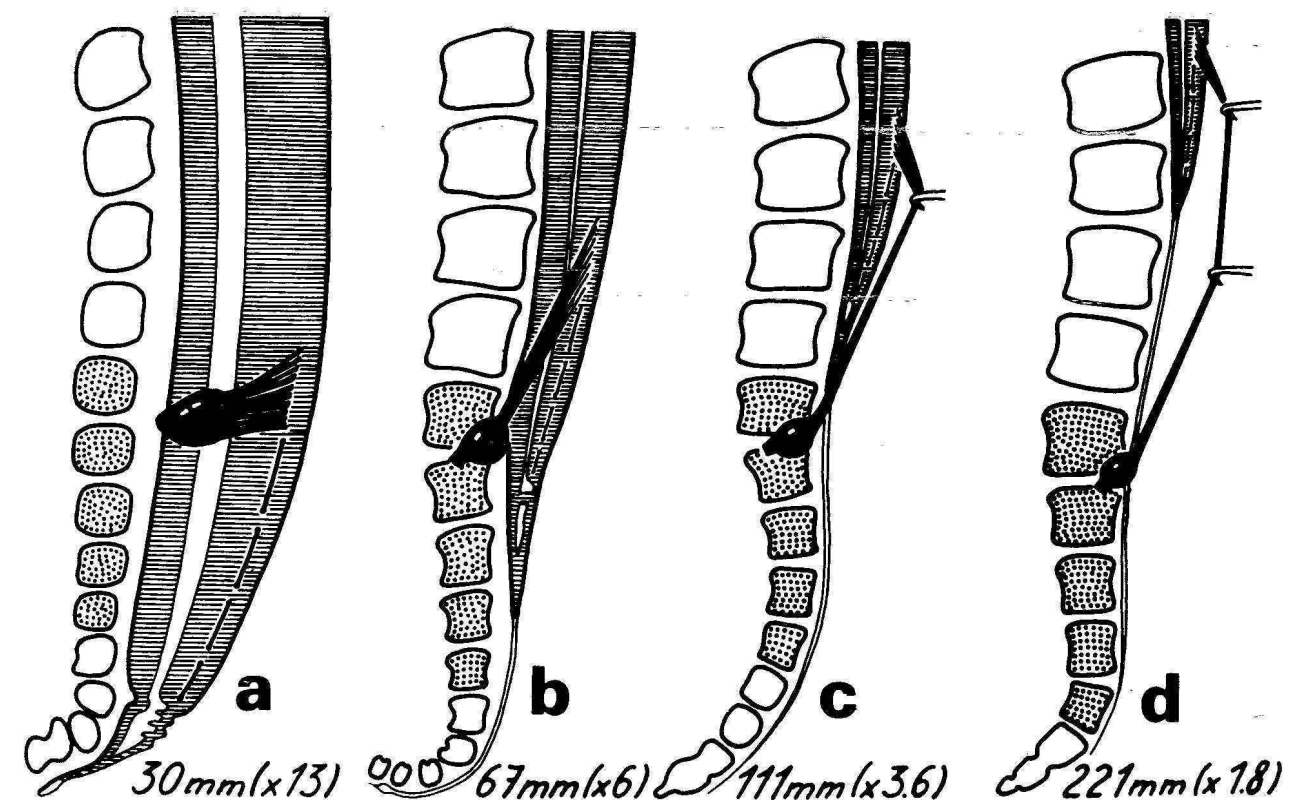


FIGURE 1. The classic diagram of the ascent of the spinal cord by Streeter (1919). Lumbosacral lordotization is related to the slower growth rate of the spinal nerve roots in respect to the faster distal growth of the vertebral column.

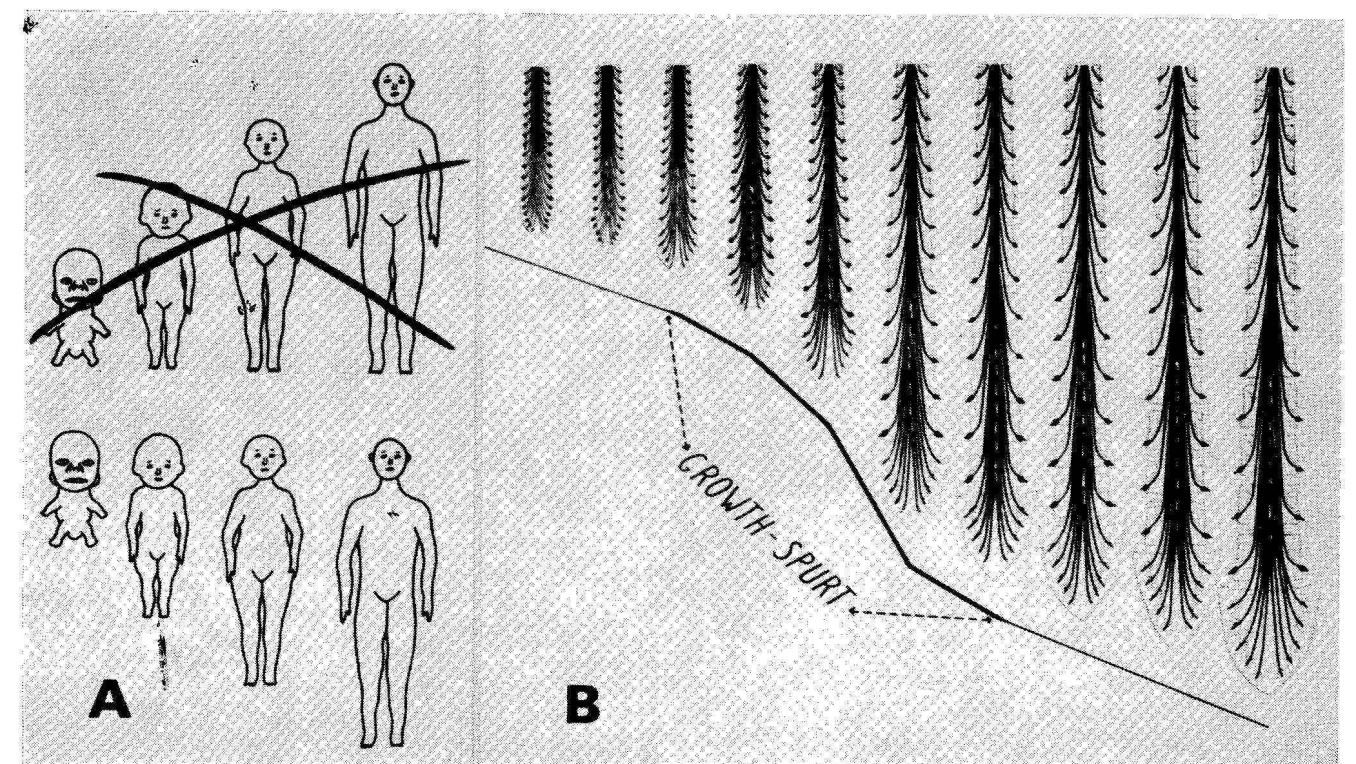


FIGURE 2A, B. Growth in length of the vertebrate body (including the growth spurts) proceeds in cranio-caudal direction (A — below) as evidenced by the distal slope of the spinal nerve roots (B).

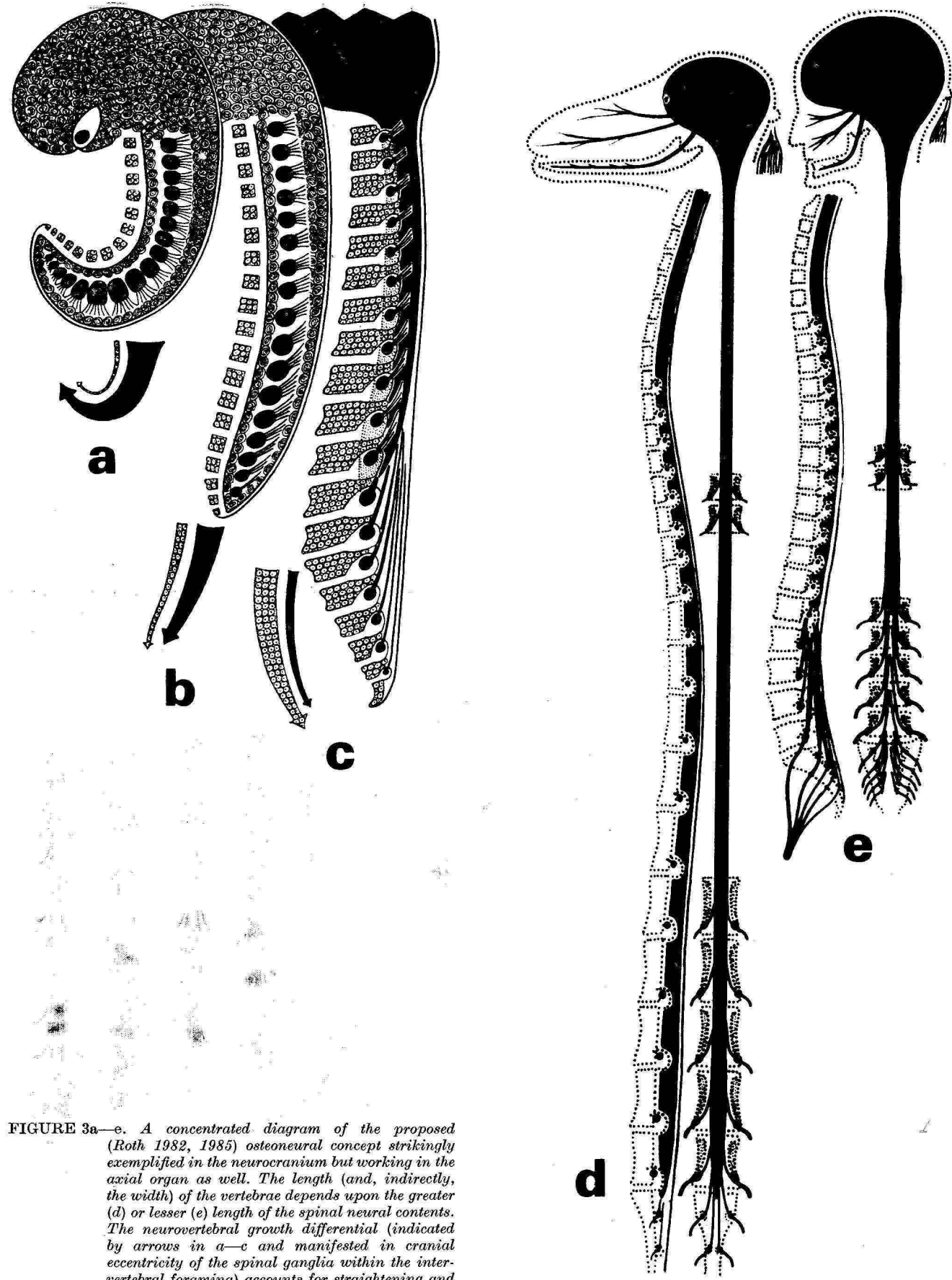


FIGURE 3a—e. A concentrated diagram of the proposed (Roth 1982, 1985) osteoneural concept strikingly exemplified in the neurocranium but working in the axial organ as well. The length (and, indirectly, the width) of the vertebrae depends upon the greater (d) or lesser (e) length of the spinal neural contents. The neurovertebral growth differential (indicated by arrows in a—c and manifested in cranial eccentricity of the spinal ganglia within the intervertebral foramina) accounts for straightening and lordotization of the originally kyphotic embryonic body.

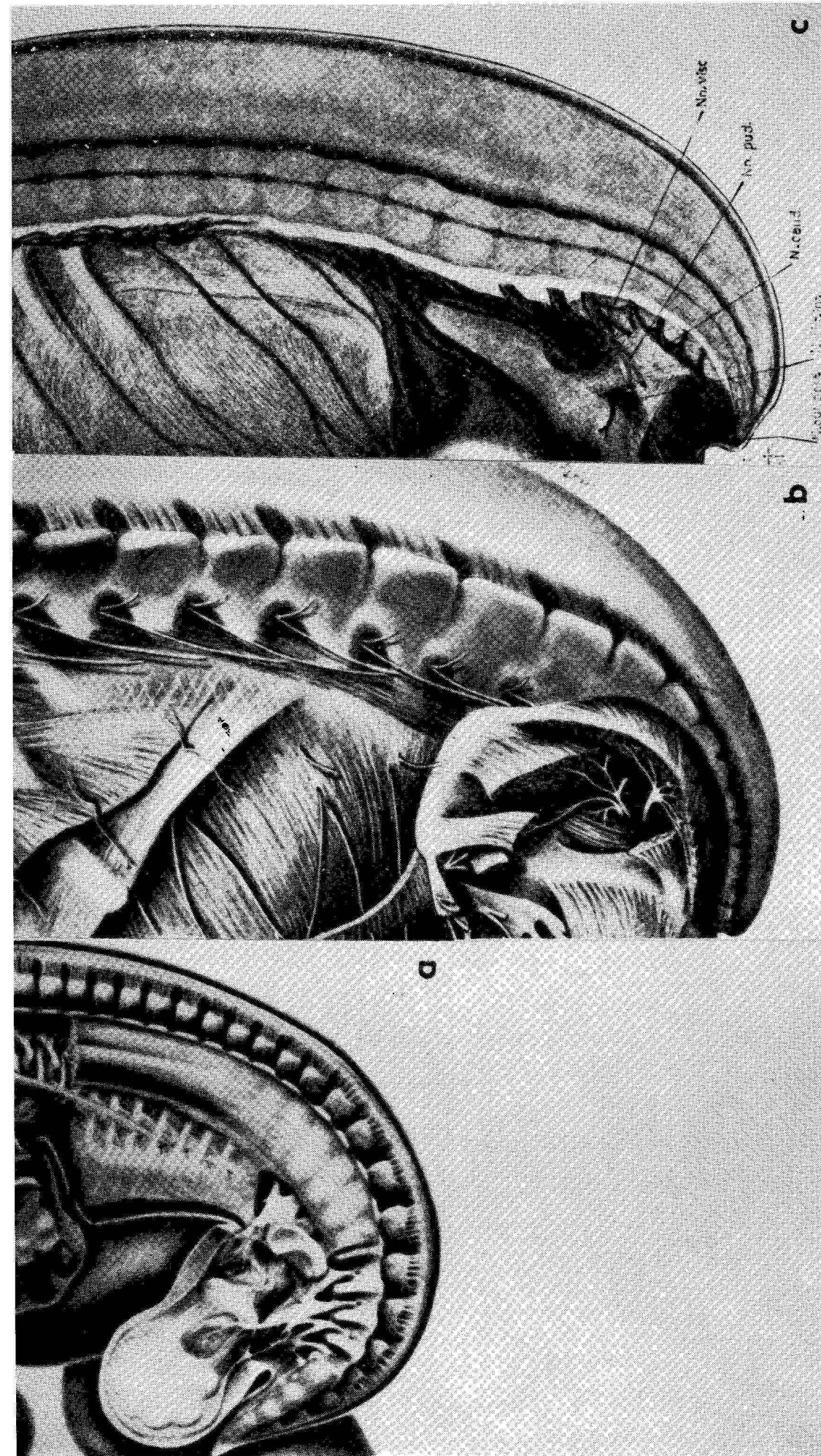


FIGURE 4a—c. The first manifestation of the promontorium in a 20 mm human embryo (c) coincidental with the onset of the neurovertebral growth differential, viz., with the beginning obliquity of the lumbosacral nerve roots (b). In the early embryo the nerve roots leave the spinal cord at right angles (a). (From Hardeen and Lewis 1901).

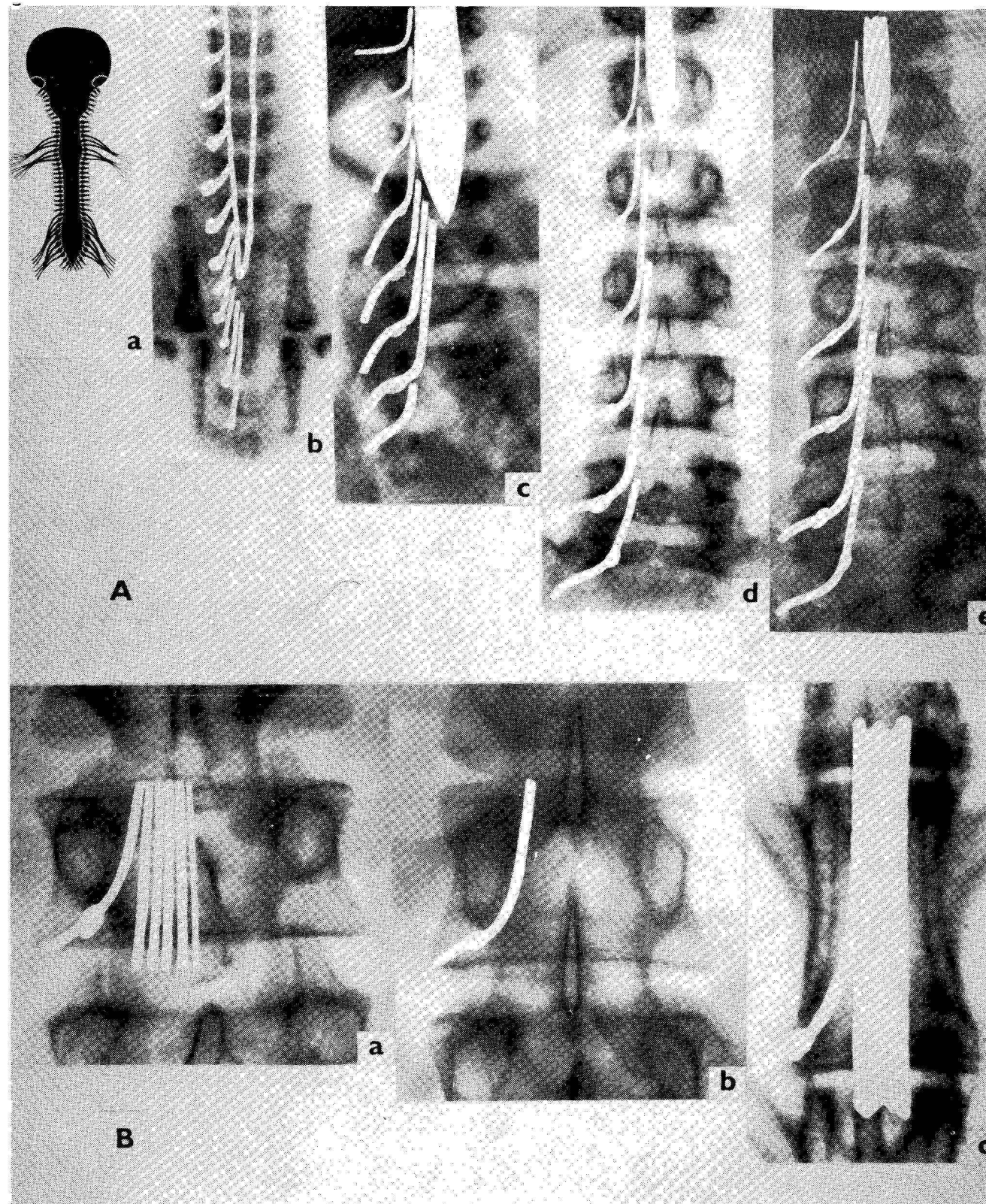


FIGURE 5A (a—e), B (a—c). Length and width of the lumbar vertebrae (roentgenograms) conceived as depending upon the growth-in-length potentiality of the nerve roots of the cauda equina (just partially drawn in).

- A) a — diagram of the early embryo consisting for the most part of nervous tissue. b — 3-week old rat with platyspondyly (i.e. short and wide vertebrae characteristic for young vertebrates including man). c — 6-month infant, d, e — adult man. To “accommodate”, i.e. to “find place” along the cauda equina, the greater quantity of bone tissue in (e) had to spread more in the transversal direction. The platyspondylic vertebrae are not axially “compressed” but short and wide, adapted to the degree of the spinal neural growth.
- B) L3 vertebrae from adult man (a — platyspondyly, b — dolichospondyly) and rabbit (c — with the spinal cord reaching into the lumbar spinal canal). In (a), the actual appearance of the cauda equina is partially indicated.

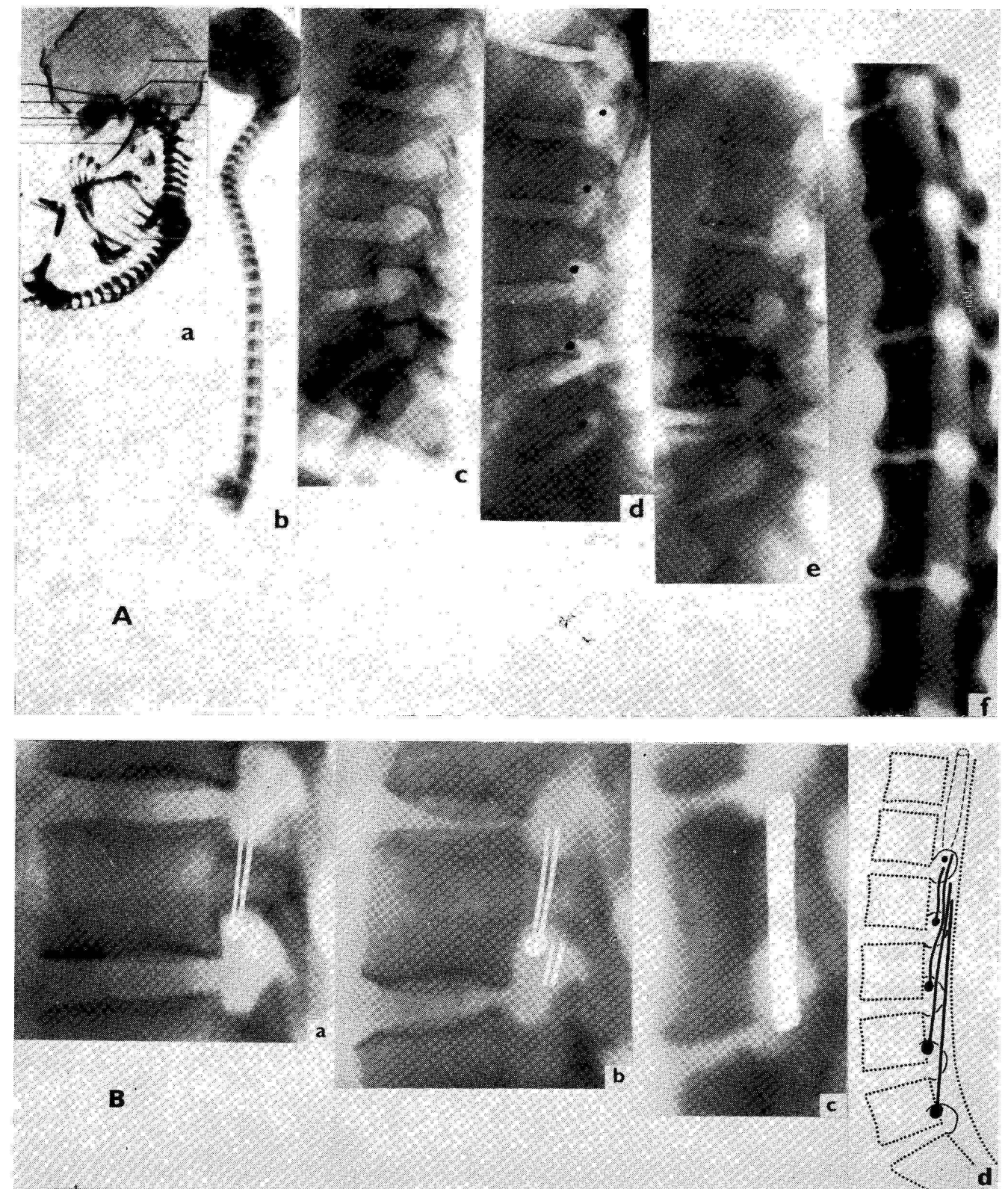


FIGURE 6A (a—f), B (a—d). The same as in Fig. 5A,B in the lateral projection.

- A) a — cleared specimen (cartilage stained) of a 50 mm human embryo (from Theiler 1963). b — newborn rabbit, c — 8-year boy, d — adult normospondylic, e — adult dolichospondylic, f — dog (tomogram).
- B) a — platyspondyly, b — dolichospondyly in man, c — rat, d — diagram showing the different relation of the lumbar spinal ganglia to the pedicles (drawn according to Jonck 1961 and shown also in the Fig. 5A—d, e and 6A—d). A lesser degree of slackening of the L4,5 nerve roots resulting therefrom has been shown also in myelographic studies (Breig and Marions 1963, Breig 1978).

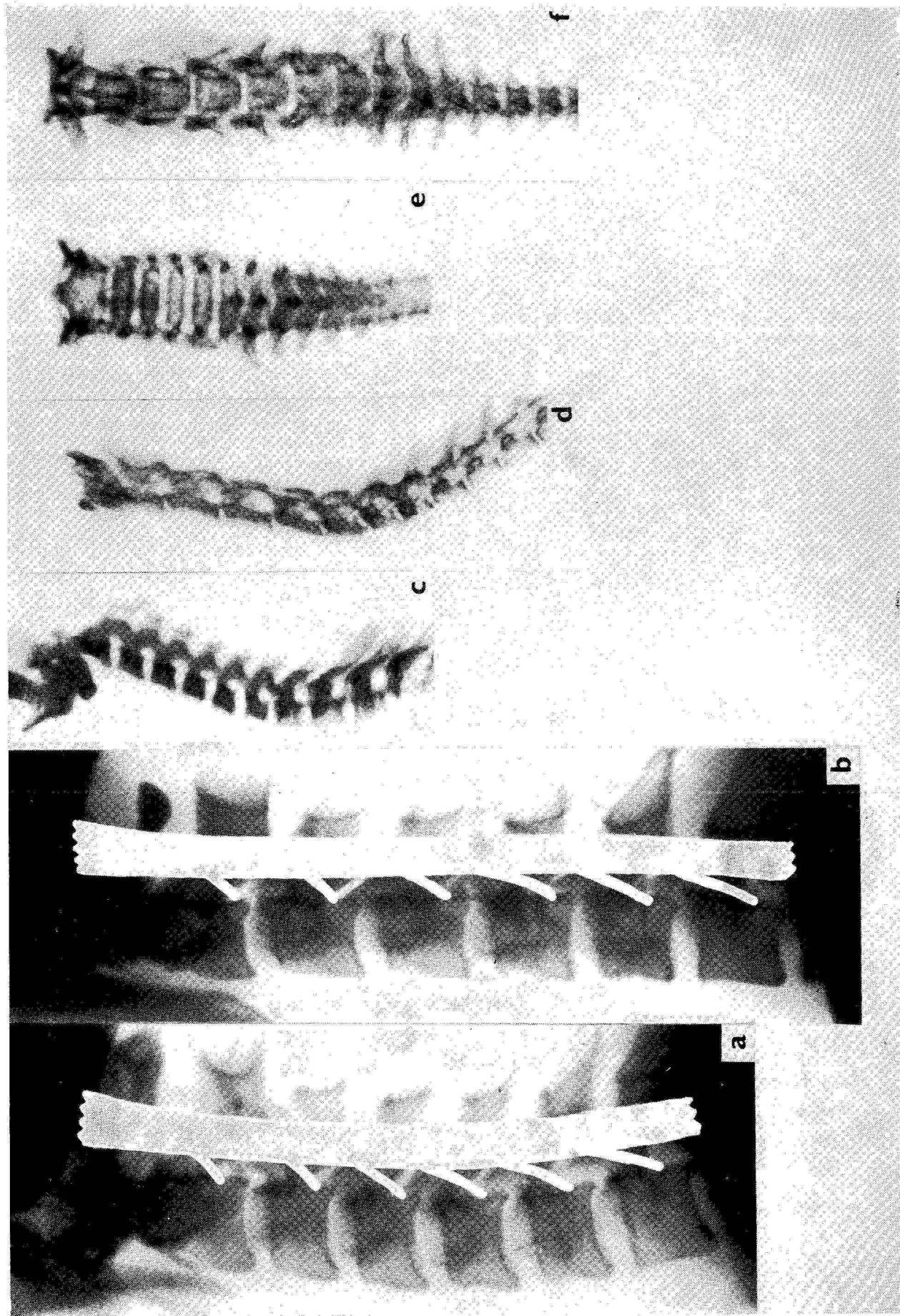


FIGURE 7a—f. Dependence of the length and width of the cervical vertebrae (roentgenograms) upon the availability of space along the cervical spinal cord. a, b — man, c, e — hedgehog, d, f — rabbit.

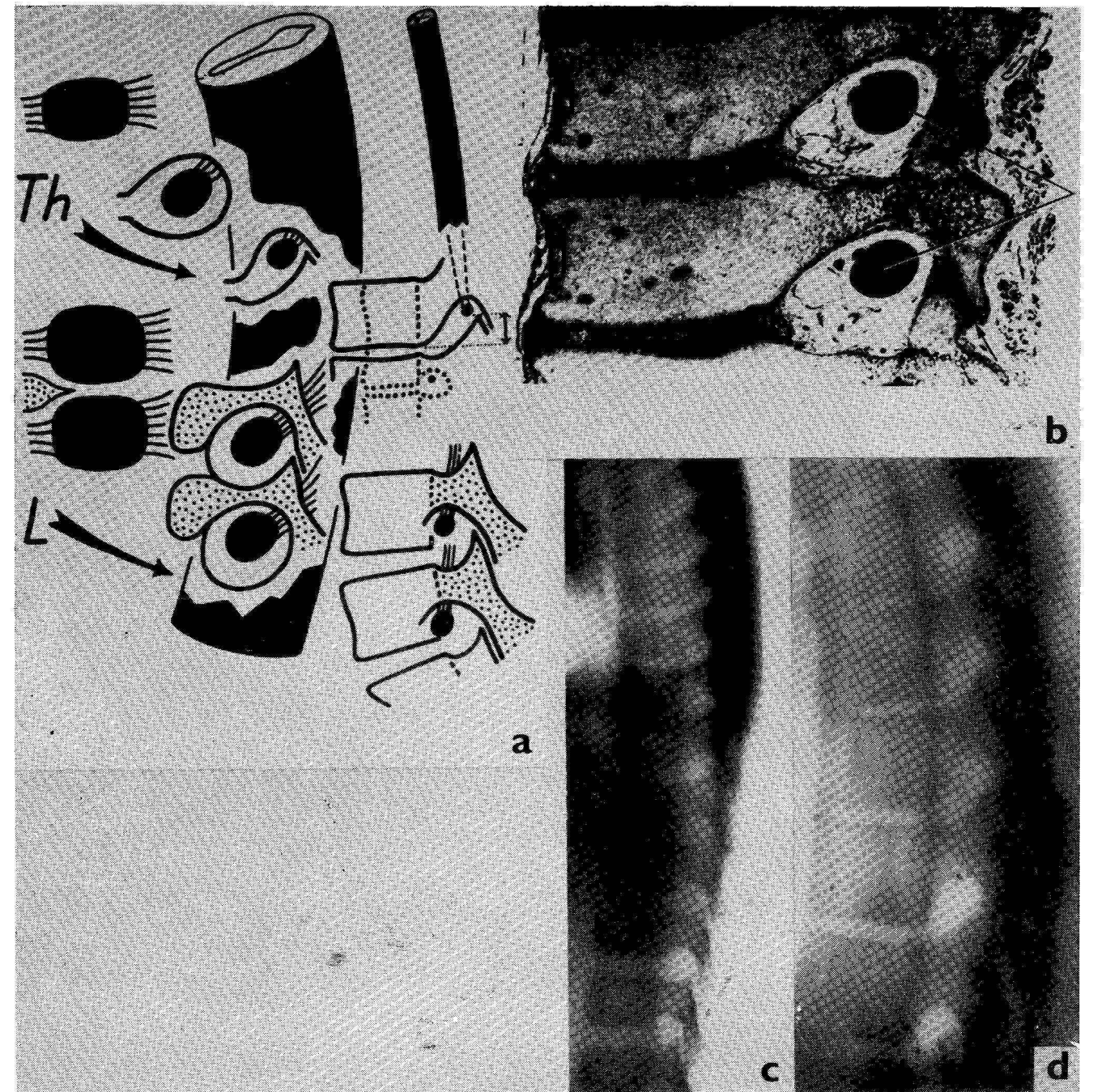


FIGURE 8a—d. Holtzer's neuroprotective mechanism in the developmental ganglio-foraminal relations. a — evolution of the pear-like shaped thoracic and kidney-shaped lumbar intervertebral foramina (by the moulding effect of the cranially-eccentric spinal ganglia) from the transversely-oval embryonic foramina (to the left — comp. Fig. 6A—a). A "tongue" of skeletogenic tissue is just growing from in front into the lumbar interganglionic space (according to Sensenig 1949). Quadruped's vertebra indicated in dots to the right. The small arrow to the right indicates the neuro-vertebral growth differential. b — thoracic intervertebral foramina with the dorso-cranially situated ganglia in a 75 mm human fetus (from Töndury 1958). — Thoraco-lumbar (c — 11-year child) and thoracic (d — adult) intervertebral foramina (tomograms).

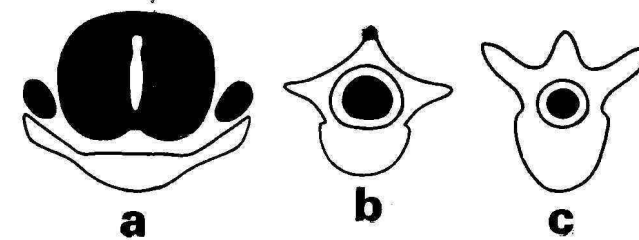
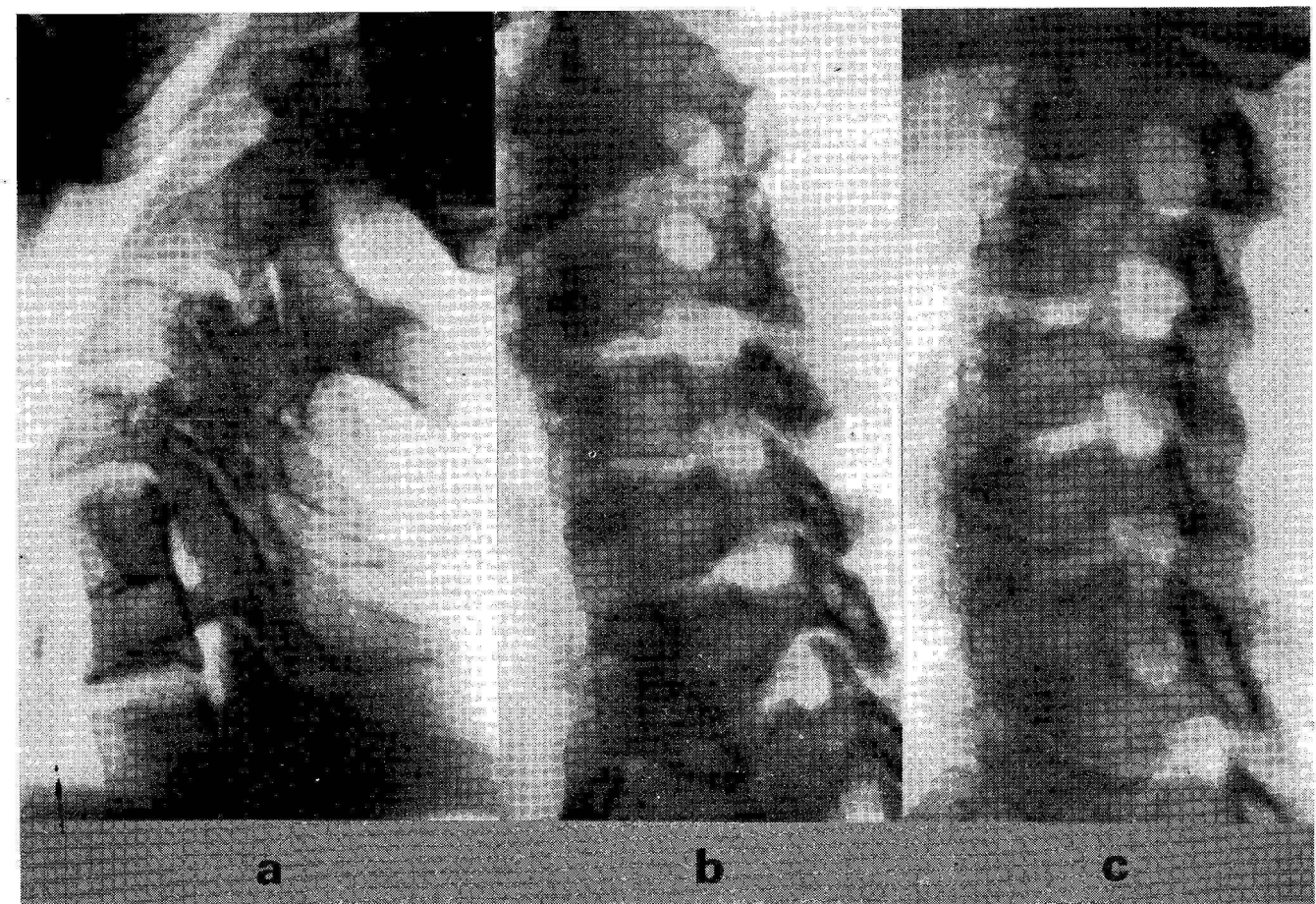
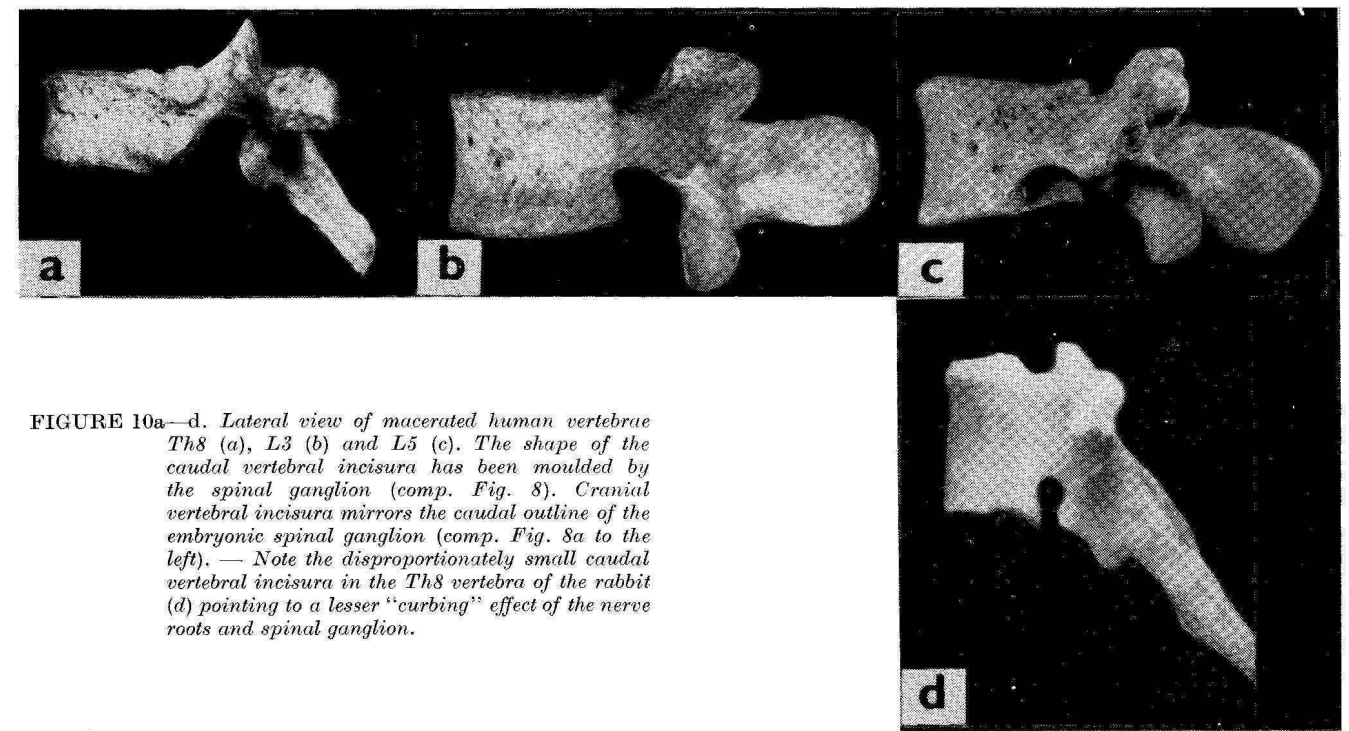
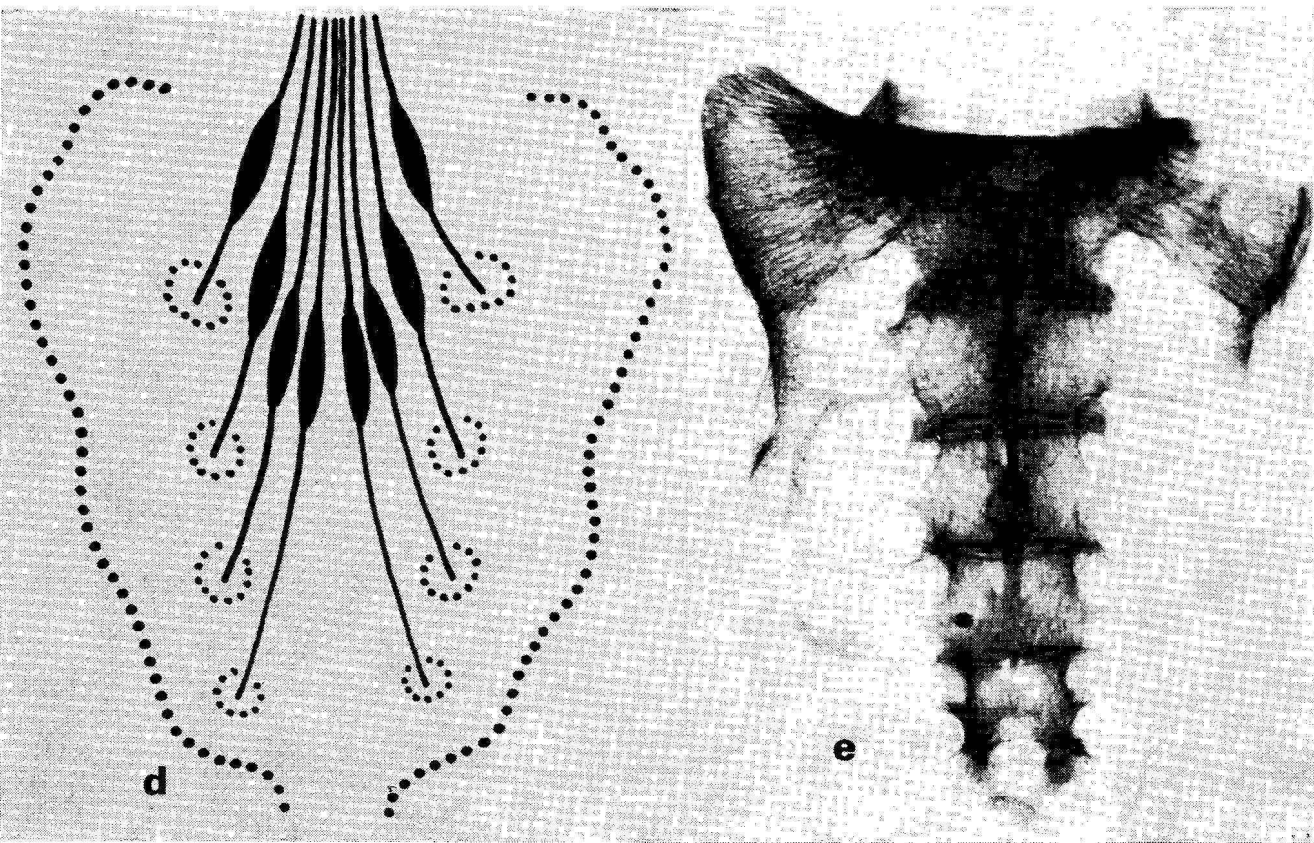
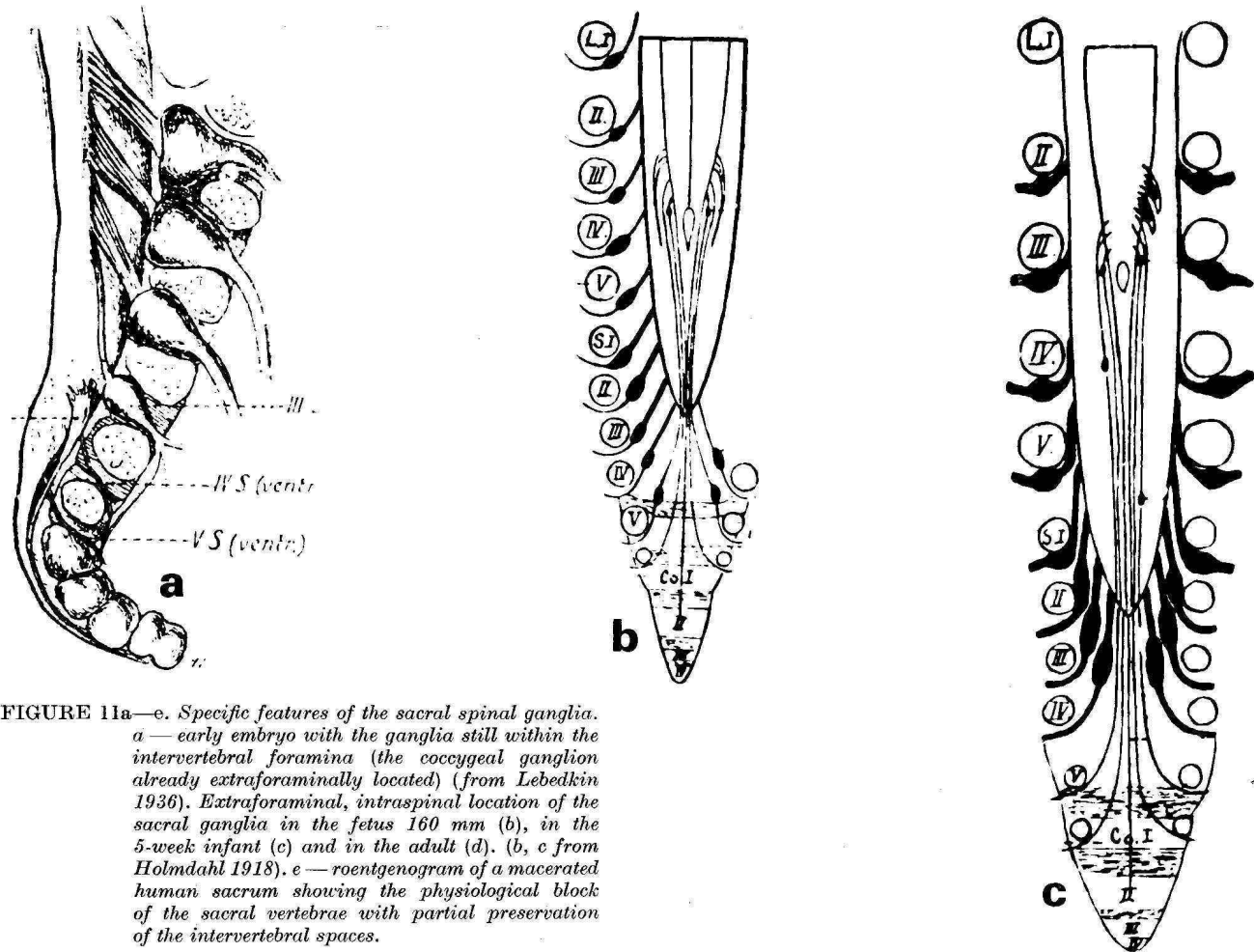


FIGURE 9a—c. Quantitative neurovertebral developmental shift demonstrated in cross-sectional diagrams of the spine. a — embryo, b — newborn, c — adult.



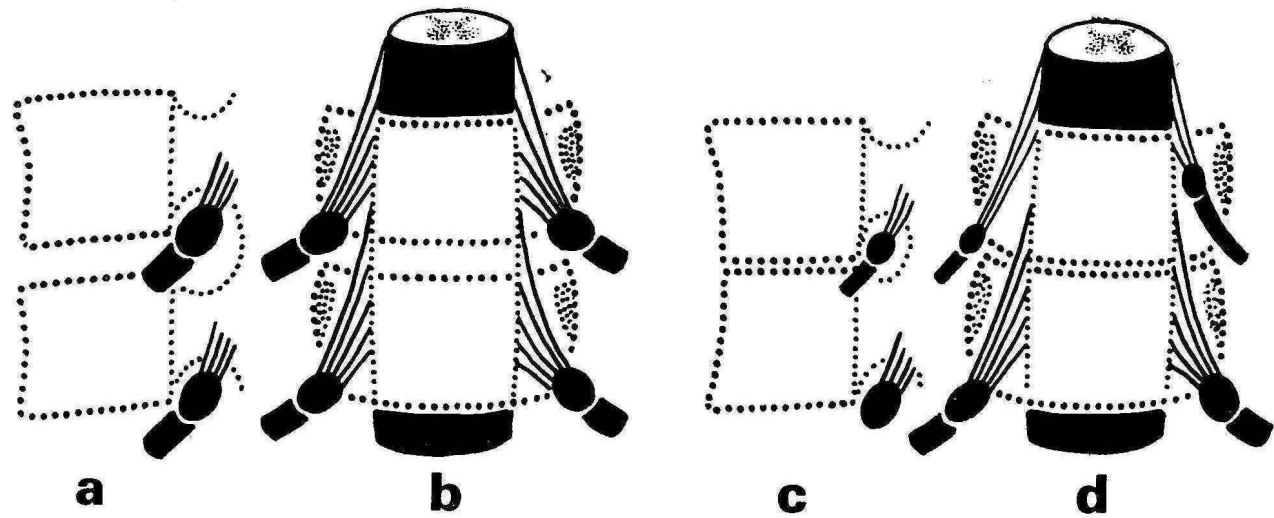


FIGURE 13a—d. Diagram of the anticipated causal relation between hypoplasia or extraforaminal location of the spinal ganglia (reflected in the reduced size of the intervertebral foramina) and developmental vertebral block(c, d). Normal ganglio-foraminal relations and normal intervertebral disc in (a, b).

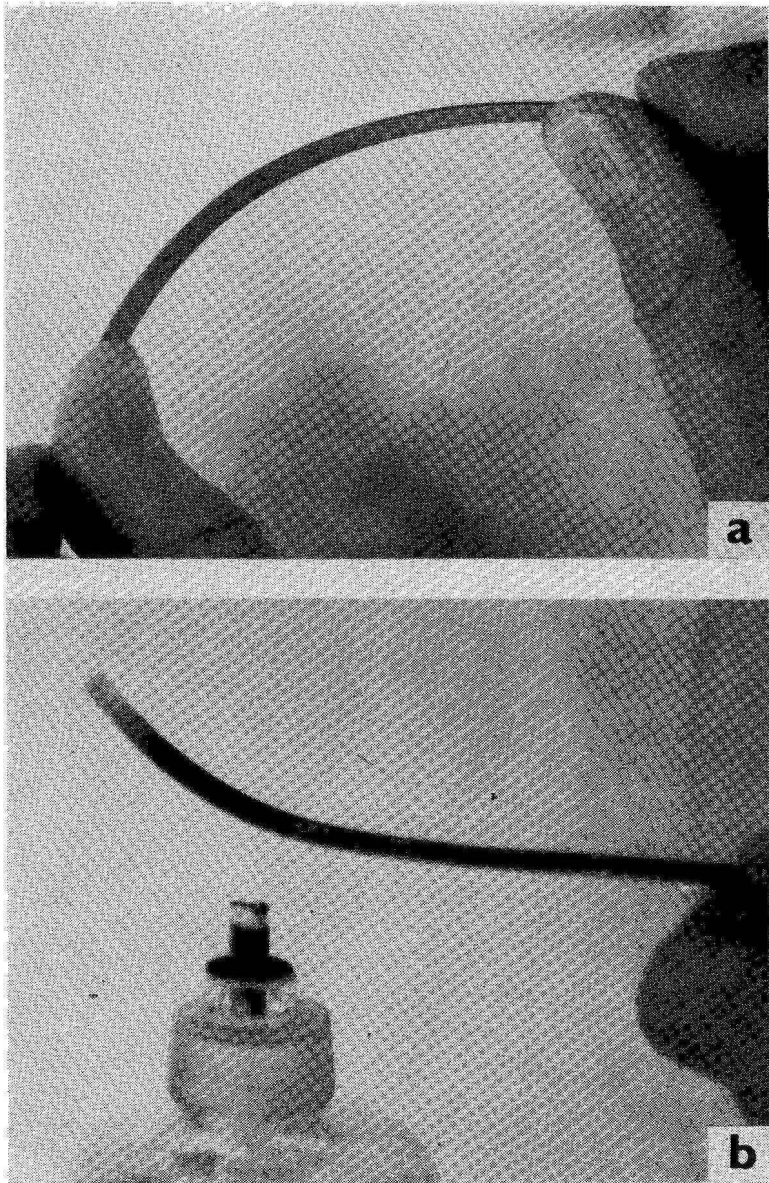


FIGURE 14a, b. A bimetallic stripe can be curved either by application of a mechanical extrinsic force (a) or by heating, i.e. by eliciting a different rate of elongation of its two components (b).

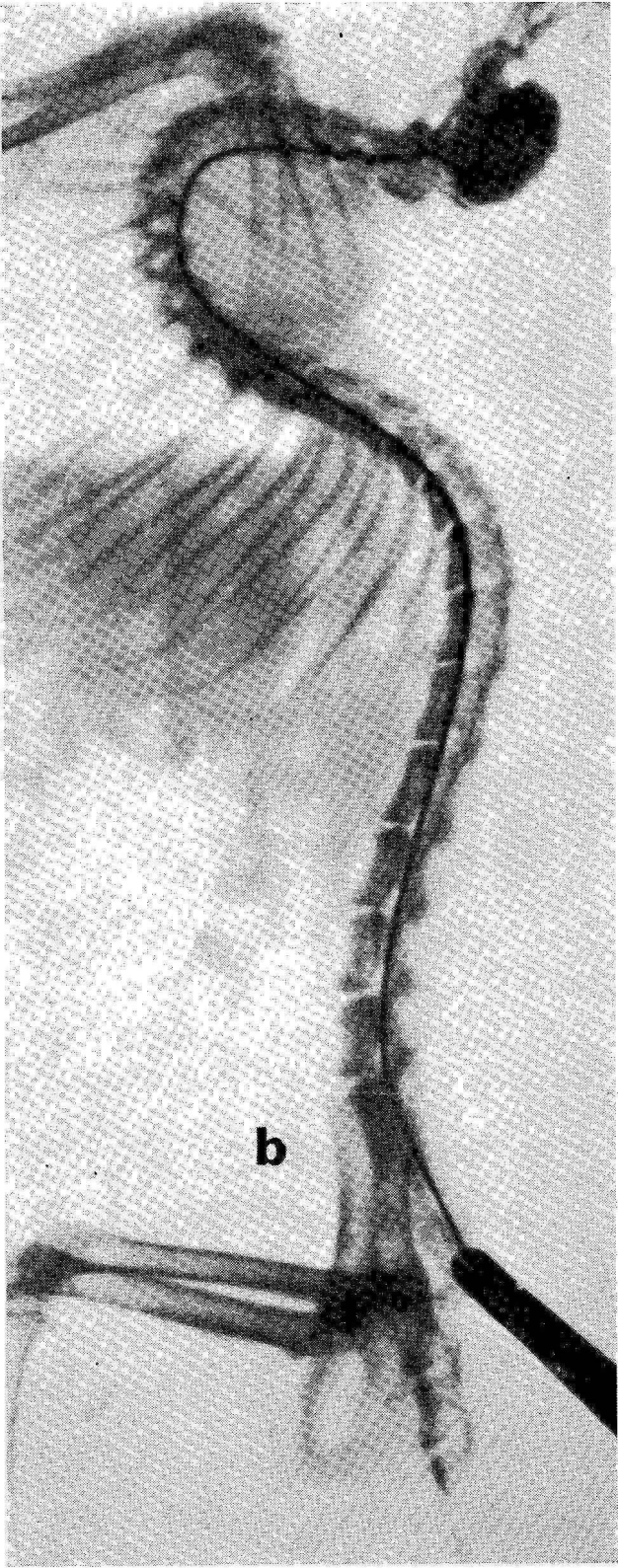
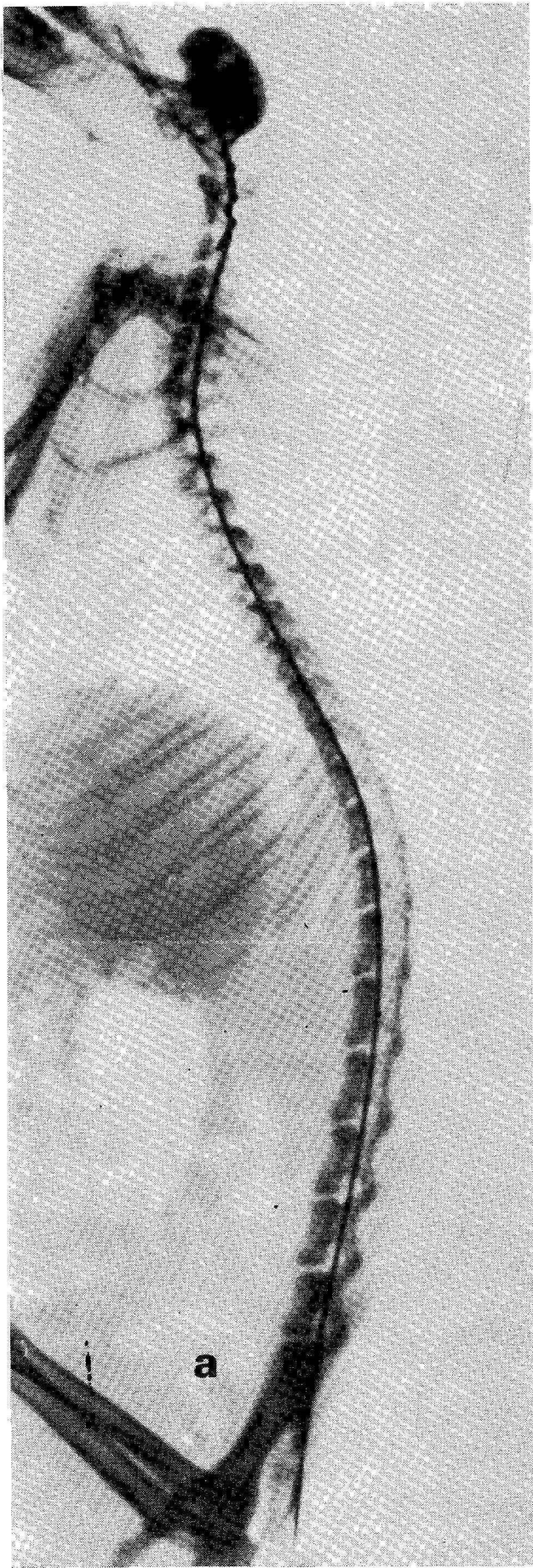


FIGURE 15a, b. Roentgenograms of rat's spine with a wire within the spinal canal fixed at the foramen magnum and representing the intraspinal nervous tissue tract. Lagging behind of the spinal neural growth imitated by shortening of the wire in (b) results in accentuation of the cervical and lumbosacral curvatures. The former is strikingly similar with the resting in vivo position of the neck in various animals (Vidal et al., 1986).

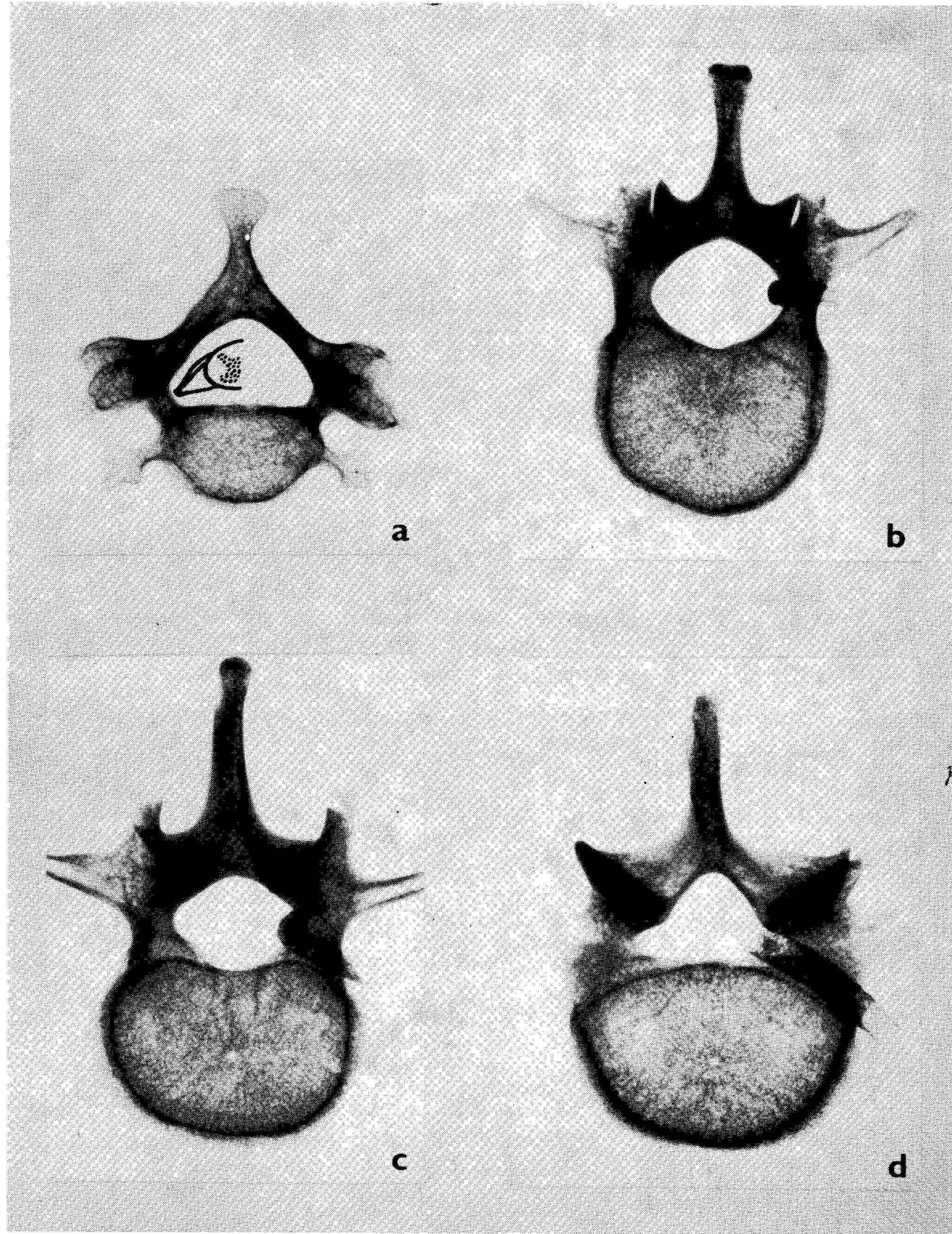


FIGURE 16a—d. Axial roentgenograms of the human vertebrae C5 (a—with the spinal cord and nerve roots partially drawn in), L1 (b), L3 (c) and L5 (d). The direction of exit of the lumbar spinal nerves is indicated by a piece of string soaked with barium mixture (to the right within the vertebral foramina).

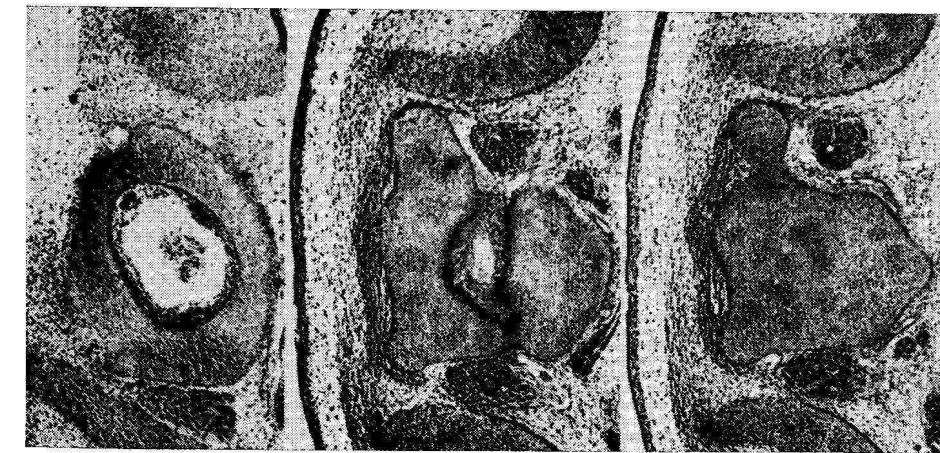


FIGURE 17. Reduction (middle) or removal (below) of the spinal cord in the chick embryo results in corresponding narrowing and obliteration of the spinal canal. (From Waterson et al., 1954).

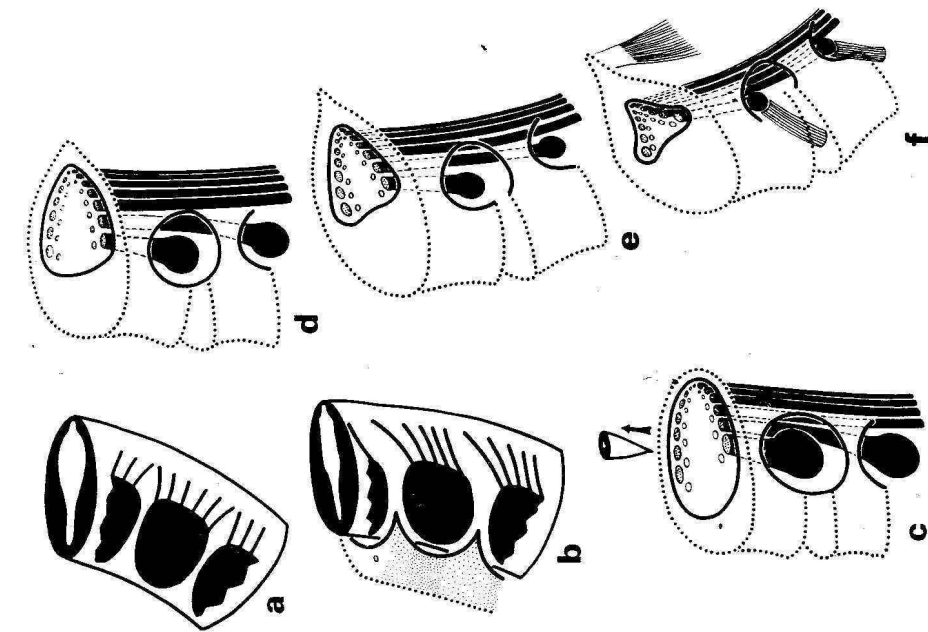


FIGURE 18a—f. Dynamics of the neurovertebral development of the shape of the vertebral foramina L5 and S1. The individual diagrams should be viewed upon as proceeding cranio-caudally under gradual change of the embryonic kyphosis into lumbosacral lordosis as a response to lagging behind of the nerve roots in (c—e) drawn according to computer-tomographic demonstration by Peterson and Harwood-Nash 1982). The notochord (b, c) is of no bearing upon the neurovertebral developmental relation (Holzer 1952a).

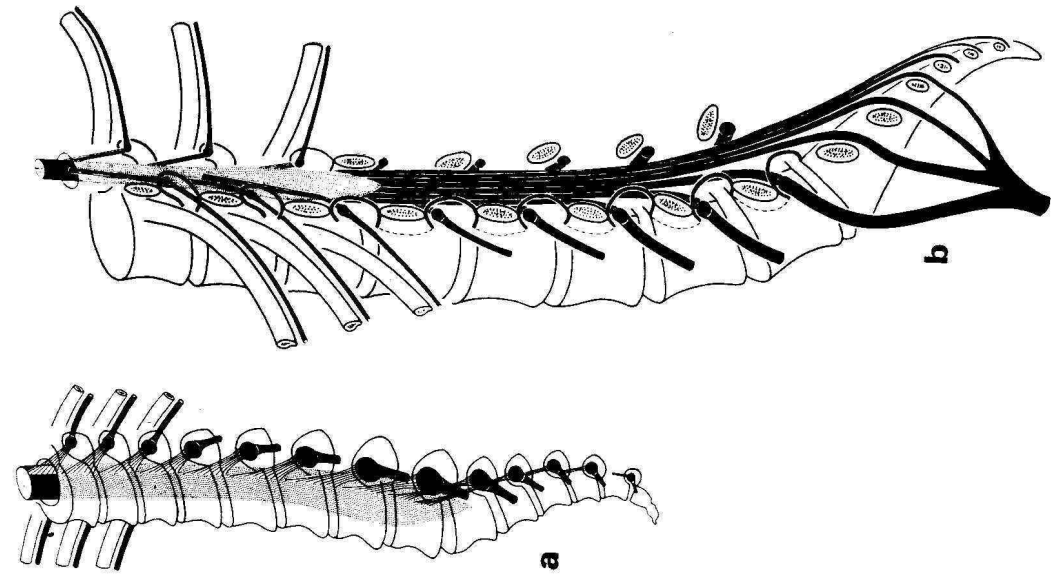


FIGURE 19a, b. A general view of the lumbosacral neurovertebral dynamics in the 100 mm human fetus (a) and in the adult (b).

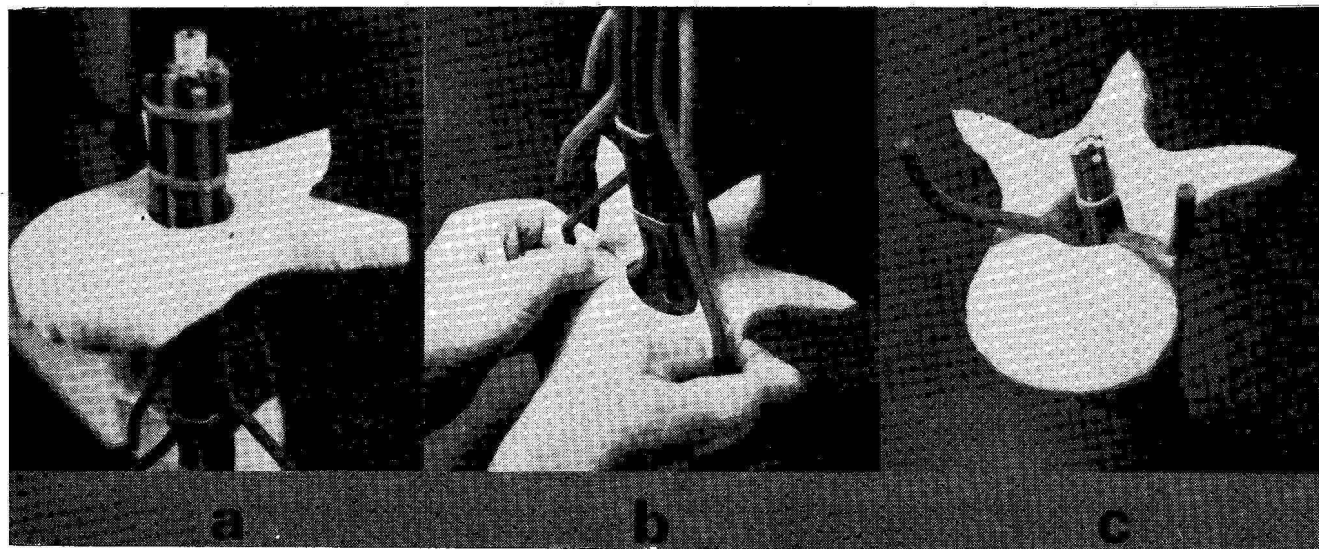


FIGURE 20a—c. Model of the cauda equina (with the ventro-lateral course of the L 4,5 "nerves") and of L1 and L5 vertebrae made of plastic material (a). Distal shift of the L5 vertebra results in triangular transformation of the originally circular vertebral foramen (b, view from below in (c)). (From Roth et al., 1976).

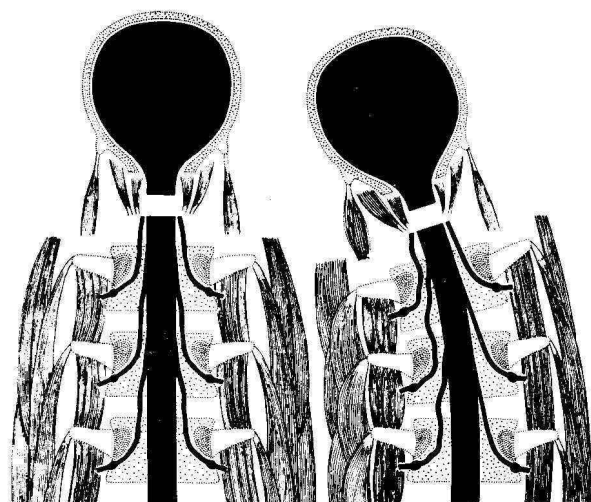


FIGURE 21. Neurovertebral versus muscular biomechanics of the spine. The neurovertebrally evolved basic shape of the axial skeleton is just modified by processes and protuberances at the sites of muscle insertions. With lateroflexion of the spine, the spinal cord preserves its median position within the spinal canal.

FIGURE 22a—c. Development of the "nervous skeleton" (Donaldson 1937) which is, however, still much denser than indicated in (c). To reproduce correctly its true extent the body should be drawn in black almost as homogeneous as that of the brain.

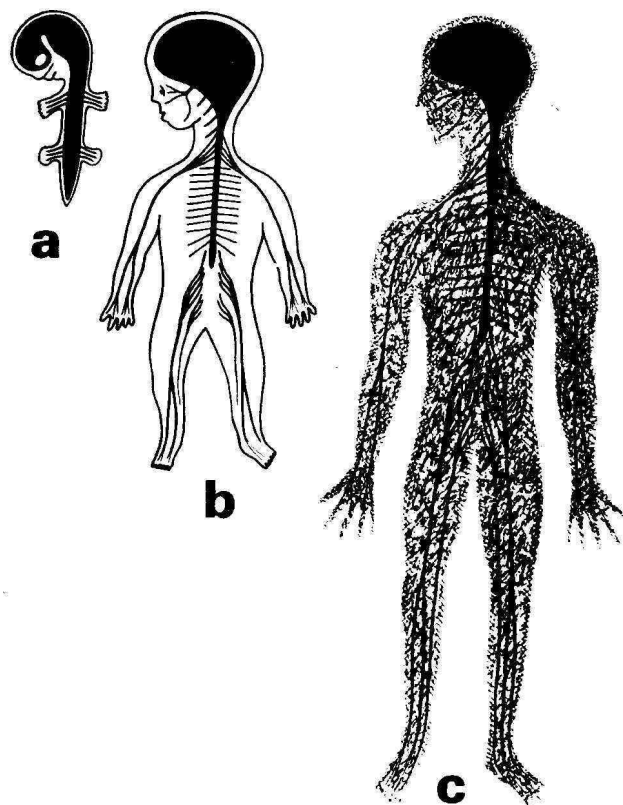


FIGURE 23a—e. The nervous skeleton, grown up from the neural primordia in the limb bud (a), indicated in the hind limbs of the frog (b) and of man (d), in the hind limb of the horse just by a single nervous trunk (e). Not unlike in the spine, the osteoneurally evolved limb skeleton is just modified by the effect of muscles (c).

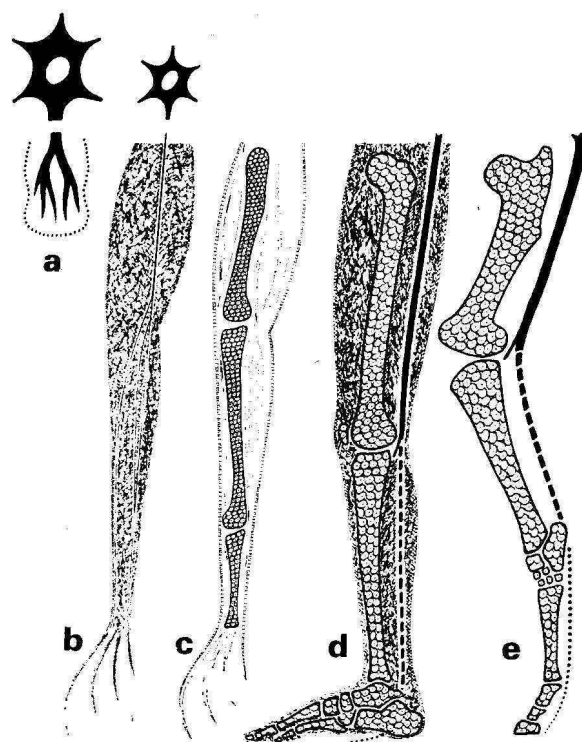


FIGURE 24a—d. The primordial nervous skeleton within the limb bud of the frog tadpole (a, b— from Taylor 1943) and the main nervous trunks in the hind limb of the adult frog (c). Growth insufficiency of the nervous trunks brought about by a skeletal teratogen results in adaptive angular deformities of bones. The straight, cord-like (in geometric sense) course of the sciatic nerve and of its branches in respect to the angulated femur or buckling tarsus suggests that the neural growth was more interfered with in the course of limb development by the administered teratogen than the bone growth (Roth 1983, 1986a). Specimens (c, d) cleared according to Williams (1943).

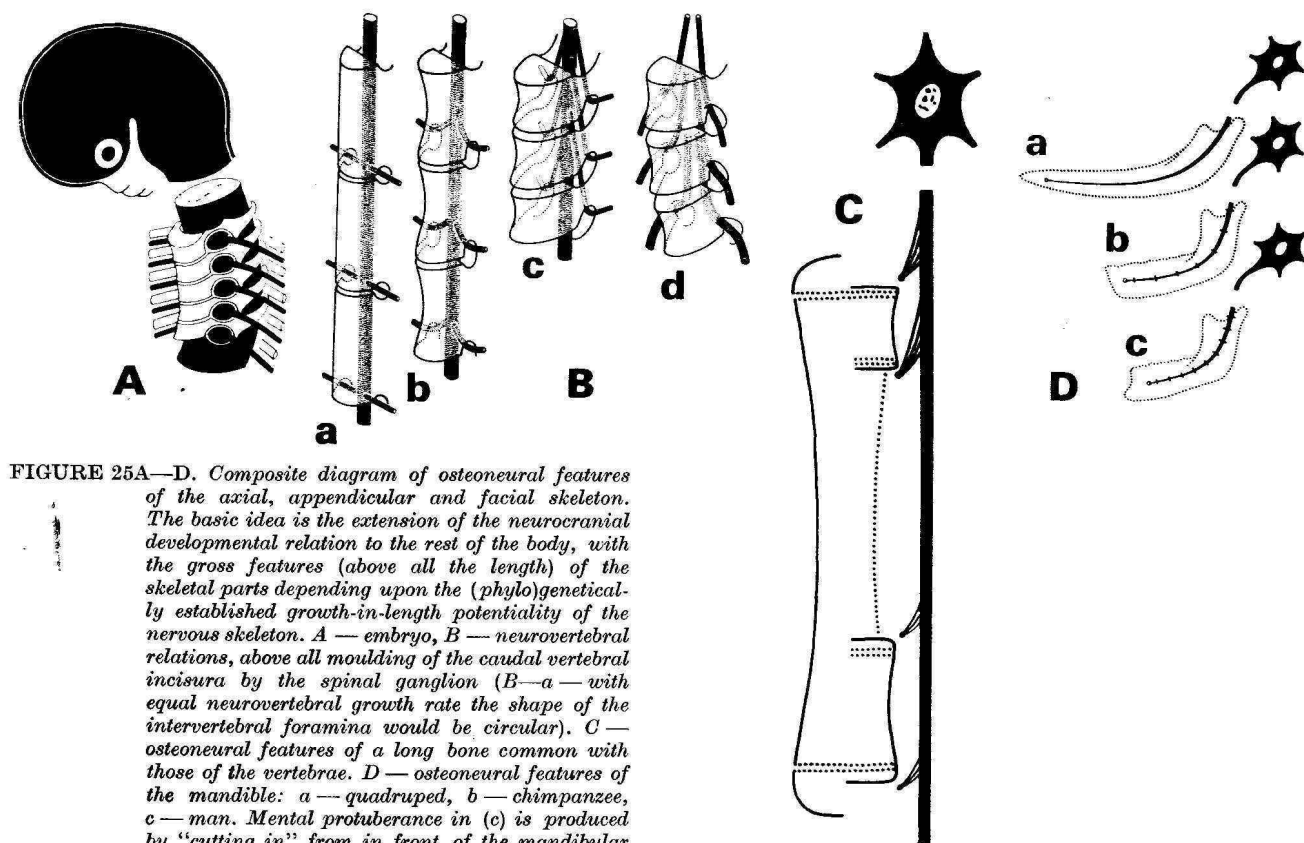


FIGURE 25A—D. Composite diagram of osteoneural features of the axial, appendicular and facial skeleton. The basic idea is the extension of the neurocranial developmental relation to the rest of the body, with the gross features (above all the length) of the skeletal parts depending upon the (phylo)genetically established growth-in-length potentiality of the nervous skeleton. A — embryo, B — neurovertebral relations, above all moulding of the caudal vertebral incisura by the spinal ganglion (B—a — with equal neurovertebral growth rate the shape of the intervertebral foramina would be circular). C — osteoneural features of a long bone common with those of the vertebrae. D — osteoneural features of the mandible: a — quadruped, b — chimpanzee, c — man. Mental protuberance in (c) is produced by "cutting in" from in front of the mandibular nervous skeleton lagging somewhat behind the bone growth. (From Roth and Krkoška 1978).

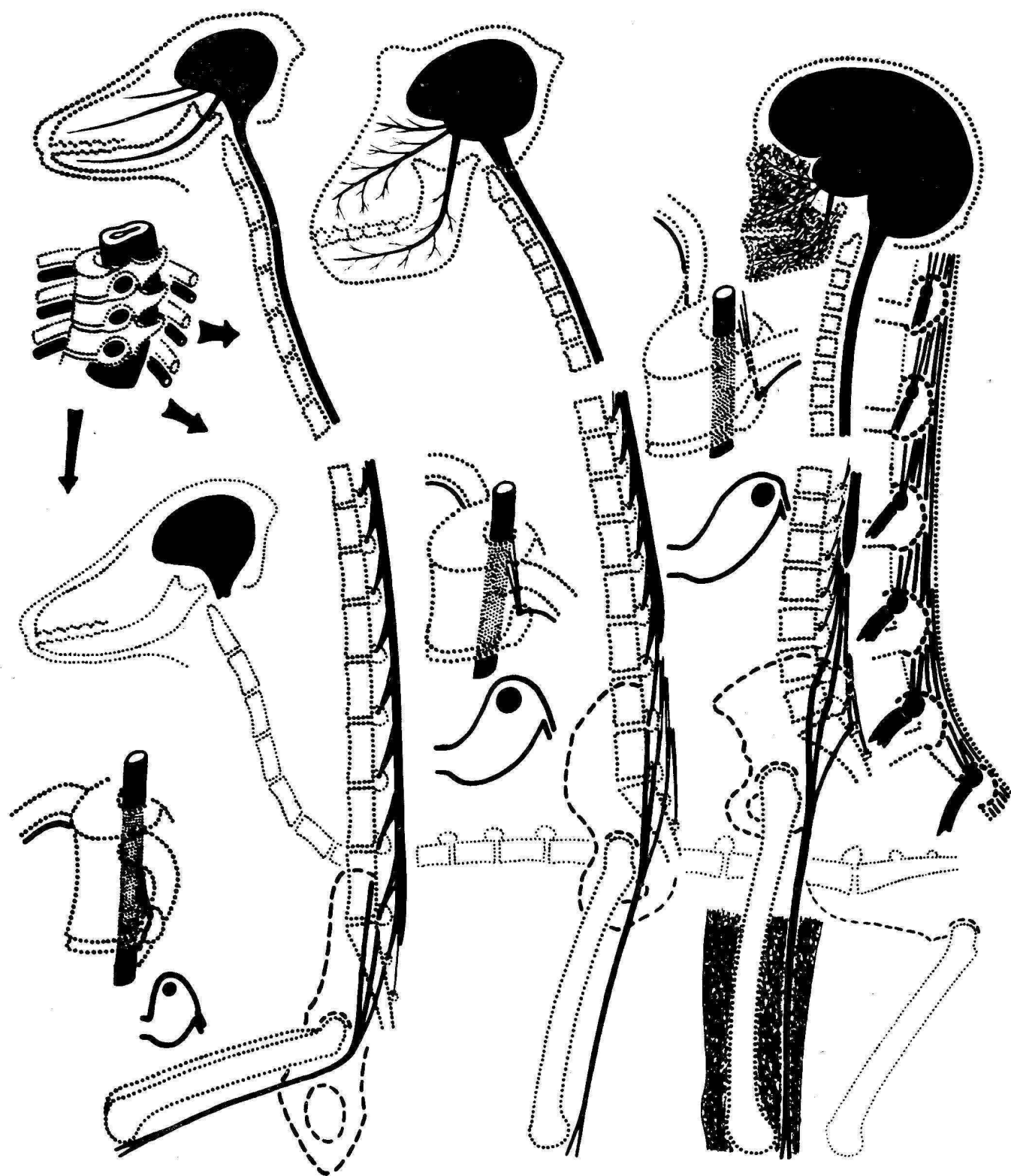


FIGURE 26. Concentrated diagram of the osteoneural concept of hominization of the skeleton the main feature of which is shortening and widening of the individual vertebrae, of the pelvis as well as of the facial skeleton. The primary event in this process is reduction of spinal and facial neural growth with adaptive shortening and widening of the respective skeletal parts. Inserts show details of neurovertebral morphology. "Reciprocal" lengthening of the sciatic and other nerves of the thigh associated with shortening of the spinal nervous tissue tract results in elongation of the human femur as compared with that of the quadruped. (Fig. 23d, e should indicate that the gross shape of bones cannot be understood by studying the individual bone cell but at the gross osteoneural level only.) — The faint silhouette of quadrupedal skeleton (below) should indicate the usual "nerveless" approach to skeletal morphology.

mals the neurocranial crests are much more prominent as well. In this sense the relative contribution of the neural and muscular factors to the morphogenesis of the neurocranium should be correctly appreciated (Klatt 1943—44; Ottow 1951). With the present situation when muscles are considered as the by far prevailing or even the only morphogenetic factor of the spine the abovementioned postulate appears still much more urgent than in connection with the neurocranium.

Concerning the shape of the human vertebral column one is prone — regardless of the various concepts aimed at explanation of the biological mechanisms which led to the erect posture — to think on the role of muscles together with something like chronic axial compression of the vertebrae by weight-bearing responsible for the human features such as shortening and widening with the circumferential girth of the individual vertebrae. These and other features, advantageous and indispensable from the viewpoint of biomechanics, have been evolved, however, in close interrelation with and in dependence upon the growth and development of the spinal nervous tissue tract. The latter, simultaneously fulfilling the role of functional mediator and morphogenetic realizer, provides for the vertebral shape most appropriate for the given species in the given environment, viz., for the unity of form and function. The stimuli from the environment as well as the effects of gravity are registered, after all, by neural exteroception and interoception. This complex information appears to be "translated" into the different growth-in-length potentiality of the CNRC in man and in the quadruped resulting in different length and width of vertebrae and in different degree of physiological curvatures of the spine. The phylogenetics of the gross spinal neural growth appears thus to represent the "missing link" between environment and skeletal morphogenesis. The role of muscles, as concerns the spine, appears to be "actually functional", not developmental. The vertical hyperlordotic orientation of the cervical vertebral column in animals (Vidal et al., 1986) (Fig. 26 below) may seem to be hardly attributable to any other mechanism than the muscular. Even in this instance, however, a neurovertebral mechanism producing a mean resting curvature of the cervical spine (similar to that produced in the model — Fig. 15b), viz., a stable and energy saving balance of the head, should be anticipated. This interpretation is further supported by the observation (Vidal et al., 1986) that with lowering or rising the head, the atlanto-occipital and cervico-thoracic junctions are predominantly involved, while the entire cervical column largely preserves its intrinsic configuration.

APPENDICULAR AND FACIAL DEVELOPMENTAL OSTEO-NEURAL RELATIONS

Paraphrasing the statement by Murray (1936) that "what is true of the bones of the limbs is likely to be true also of other cartilage-replacing bones of similar general character" one is led to the conclusion that what is true of the vertebrae — including the neuro-vertebral developmental relation — is likely

to be true also of the limb bones. The vertebral body grows in length by enchondral ossification at the cranial and caudal cartilaginous end plate. It may be conceived of as a very "short" long bone lacking the diaphysis, with the two metaphyses fused directly each other and with very flattened epiphyses (Fig. 25C). In the longer vertebrae of quadrupeds, epiphyses are less flattened so that the vertebral body (above all the cervical in long-necked animals) resembles rather closely a growing long bone (Beadle 1932). In view of the rather loose spatial relation of the limb bones to the nervous trunks there would seem difficult, however, to accept any osteo-neural developmental relation analogous to that exemplified in the neuro-cranial and neuro-spinal relation with the nervous and the skeletal components developing in the most intimate vicinity.

Concerning the morphology of the peripheral nervous system there prevail two quite different and fragmentary notions, viz., the gross-anatomical and the histological. The former takes into account just the main nervous trunks and their gross branches as indicated in anatomical diagrams by branching lines (Fig. 22b). The latter approach is focused on the terminal nervous twigs, above all on the nervous terminations in various organs as seen in a histological section. The peripheral nervous system in its entirety represents, however, an extremely dense feltwork of nervous trunks, branches and fibres which would persist and delineate the shape of the body even if all the other non-nervous tissues would disappear and which was called "the nervous skeleton" (Donaldson 1937). The nervous skeleton, still almost absent in the embryo, has attained a tremendous extent together with the bodily growth (Fig. 22a—c). Instead of just following passively the outgrowth of the bodily parts, however, the nervous skeleton represents a *limiting framework* for the outgrowth of the other, non-nervous tissues, viz., the nervous skeleton is "stuffed" with the other tissues rather than permeating them passively. The density of the nervous skeleton is much higher than that indicated in Fig. 22c — to show its real extent would require to depict it in black almost as homogeneous as that of the brain. There exist at present no technical means how to demonstrate the nervous skeleton as a whole in a similar way like, for instance, a corrosive specimen shows the injected capillary bed. The nervous skeleton, an incontestable anatomico-histological fact, can be just reconstructed in mind.

As a matter of fact, the relation of the limb bones or of the jaws to the nervous system is still more intimate than that of the neurocranial capsule to the brain. The limb bones and the jaws should be conceived as extending among and/or along the nervous trunks, the macro-representative of the nervous skeleton. The latter, permeating the richly "innervated" periosteum, forms a dense feltlike neural envelope on the surface of every bone. Any developmental change of a bone, above all its growth in length, cannot take place and be thought apart from the surrounding nervous skeleton.

This fairly provocative view finds an important support in experimental skeletal teratogenesis. "Skel-

etal" teratogens are mostly respiratory inhibitors believed to interfere in some unknown way with the normal bone growth. Among the tissues growing in length within the developing extremity the nerves represent, however, the most vulnerable structures the growth of which should be expected to be more profoundly compromised by the administered "skeletal" teratogen than any other growing component including the bones. Stereotyped angular deformities of bones which may be produced in experimental animals (Fig. 24d) by a great number of teratogens seem to represent just adaptations of the growing bones to the growth insufficiency (i.e. to abnormal shortness) of the nervous trunks (Roth 1974, 1982, 1983, 1985, 1986). One could argue without much exaggeration that, not unlike the saucer-like shape (a "quasi-deformity") of the neurocranium is derived from the growing central nervous structure, the deformity of the limb bones shown in Fig. 24d results from their gross adaptation to the inadequately growing sciatic nerve and its branches.

RECIPROCITY OF THE NEURAL GROWTH AND THE SKELETON: A SUGGESTION

Bardeen (1907) has pointed out that nerves grow as plants grow and that extensive growth of one nerve tends to retard its neighbours, lack of development tends to excite them to more active growth. This fairly common neurobiological phenomenon seems to work, for instance, in the reciprocal growth relation between the brain on the one hand and the spinal cord and facial nerves on the other hand. Weindenreich (1948) when considering the relative shortness of the human spinal cord in contrast to that of other mammals, suggests a sort of "swallowing" of the spinal cord by the enhanced development of the brain. The same seems to apply to the nerves of the human facial area with their limited growth-in-length potentiality in contrast to those of the animal (Fig. 3d, e; 25D; 26). Shortening of the CNRC in the course of hominization has been associated with lengthening of the sciatic nerve which, on the other hand, is accompanied by short nerves of the foot. These are just a few examples of the neural growth "reciprocity" shown in the pelvic limb of the frog, man and horse (Fig. 23a—e) but encountered in many other mammals, birds and amphibians.

In view of the dependence of the vertebral length upon the length (i.e. upon the extensive-growth-potentiality) of the enclosed neural contents, the various length of the limb bones hardly can be considered as independent upon the enveloping nervous skeleton, viz., as a primary intrinsic parameter of the growing bones. It would mean to adhere to the notion of passive neural growth which just follows the outgrowth of bones — a notion equally untenable from the neurobiological point of view like that considering the spinal nerve roots as simply following the outgrowth of the spine. Gregory (1928) pointed out that limb proportions were not fixed, eternal things, laid down once for all and delivered to us, but that they were subject to change in the course of evolution. In animals which leap, the distal segments of the limbs

were elongated; in those which do not leap, but which merely run or walk, it is the proximal segments of the limbs which are elongated. Behind these gross changes of bone length one should disclose the elusive primary "reciprocal" changes of length proportions of the nervous trunks and of the nervous skeleton; the bones "filling in", as a matter of fact, corresponding "cavities" within the nervous skeleton are just "carried with". Even the shortening and broadening of the pelvis in the course of hominization should be viewed upon as reflecting the primary growth reduction of the enveloping nervous skeleton and of the massive lumbo-sacral nervous trunks (Fig. 5A—b; 26).

Changes in length proportions of the facial skeleton, above all shortening of the mandible associated with hominization, cannot escape the principle of the osteoneural developmental relation. Phylogenetic shortening of the mandible just reflects the primary length reduction of the mandibular nerves and of the entire mandibular nervous skeleton. The dorsally directed hypothetical pull exerted on the frontal portion of the mandible postulated, for instance, by Schuricht (1952) to explain the appearance of the chin, appears thus to be effectuated by the shortened nervous skeleton "cutting in" from in front into the somewhat faster growing mandible resulting in the characteristic concavity of its ventral surface and in production of the mental protuberance (Roth and Krkoška 1978) (Fig. 25D). The term "cranio-facial growth" does not imply two different types of bone growth, a neuro-dependent and the other neuro-independent, but just one type of growth, cranial and facial, with the respective skeletal parts partly adapted to, partly restricted by the extent of the nervous skeleton.

DENERVATION AND EXPLANTATION EXPERIMENTS ON BONE GROWTH: ELUSIVE ASPECTS

Experiments showing a fairly normal development of an explanted or denervated bone primordium, viz., pointing to an independence of the skeletal growth and development upon the nervous system have deeply influenced the established opinion concerning, above all, the presumed self-regulatory character of growing limb bones. These experiments, despite their ingenuity, imply a fair deal of unhistorical approach. An "acute" denervation or explantation performed in the course of individual ontogenesis can be hardly of any bearing upon the phylogenetically established osteoneural features of a bone which will develop on the whole normally by (phylo)genetic inertia even in the absence of nerves. Still another example may illuminate the indispensable caution when evaluating the results of denervation experiments: An explanted fetal neurocranium or a part of it certainly will continue to grow in an appropriate medium under preservation of its saucer-like shape imparted to it originally by the "kiss" of the growing brain. The absence of the latter in the explant by no means does warrant the inference of a neuro-independent development of the neurocranium, not unlike in the development of the fish brain and neurocranium (p. 74).

CONCLUSION

The presented analysis of the gross neurocranial, neurospinal and osteoneural developmental interrelations suggests that the gross features of the skeleton, indispensable from the viewpoint of biomechanics, have been evolved in the most intimate interrelation with and in dependence upon the gross growth and development of the spinal and peripheral nervous structures. The nervous activity of vertebrates is characterized by a continuous and irreversible "reorganization" induced by the environment and lasting from birth to death (Csányi 1982). The more complex is the nervous system, the longer is the time while excitation produced by the external stimulus is stored in the structure of the brain (Csányi 1982). These aspects of neurophysiology are being considered exclusively in connection with evolution of behaviour and mental activity, viz., with the neural functions. They seem to involve also, however, "reorganization" of the neural growth during the time abysses of phylogenetic development with a clear-cut impact upon the gross morphology of the skeleton. In addition to classic neurotrophism controlling vital basal functions of tissues at micro- and infrastructural levels, the impairment of which results in "neurotrophic osteoarthropathies" (Fried 1979 a.o.) there exists a "macro-neurotrophism" effectuated by mediation of the gross neural growth and providing for the appropriate skeletal shape. The role of vessels is just to maintain the bone metabolism — a vitally important function which, however, has nothing to do with the evolution of the skeletal shape. It seems self-evident that the length of the vertebrate body is determined by the length of its skeleton with the length of the soft parts including the nerves just adapted to the length of bones. In the light of the osteoneural concept, however, the well-known saying "The organism lives so long as its neurons" should be paraphrased as "The organism — including its skeleton — grows up to such a length as its neurons".

Every skeleton or its part demonstrated in the roentgenogram, deposited in the osteological museum or recovered at the archaeological site should be viewed upon — in addition to being surrounded by nutrition-providing blood vessels and capillary bed as well as by muscles setting them in function — as though "immersed" into the felt-like form-giving nervous skeleton. As concerns relation to the bony skeleton, the extremely intricate neural functions should be entirely disregarded and just the neural growth should be taken into consideration, i.e. the osteoneural developmental relation exemplified in the neurocranium should be extended to the entire body. By evolution of the brain, viz., by its enhanced growth the human features of the neurocranium were brought about. Hominization of the rest of the skeleton should be related to peculiarities of the spinal, peripheral and facial neural growth.

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MUDr. Milan Roth, CSc.
Radiodiagnostic Clinic
Medical Faculty Hospital
J. E. Purkyně University
Pekařská 53,
656 91 Brno
Czechoslovakia