OBSERVATIONS ON THE POSTNATAL STRUCTURE OF THE INTERVERTEBRAL DISC IN MAN

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INTRODUCTION

The human intervertebral disc has long attracted the attention of anatomists. The earlier descriptions referred only to the macroscopic appearance. Later, with the development of improved technical methods, its microscopic structures received consideration. Vesalius (1543) referred to and figured the discs *in situ*, Bartholinus (1668) described these structures as 'gristles', and Winslow (1776) gave a more detailed account of the macroscopic appearance of the disc. Luschka (1856) described the anatomy of the discs at the extremes of life, and in his monograph on the hemiarthroses (1858) gave a detailed description of the macroscopic and microscopic structure and again referred to the changes seen at birth and in old age. Humphrey (1858) designated these structures 'intervertebral substances', described the arrangement of the fibres in the annulus fibrosus, noted the relative avascularity of the disc tissue and commented on the varying thickness of the discs in the different regions of the vertebral column. Henle (1872), Poirier & Charpy (1899), Fick (1904) and Petersen (1930) give good, well-illustrated descriptions of the disc with some reference to age changes. Schaffer (1910, 1930) refers to the disc in connexion with his studies of the notochord, Übermuth (1929, 1930) describes conditions present in certain decades, and Böhmig (1930) describes the structure in certain age groups in his studies of the vascularization of the disc. The monograph of Beadle (1931) is devoted to detailed descriptions of the macroscopic and microscopic anatomy of the disc, and to changes in the structure of the discs connected with certain pathological conditions of the spinal column. In the text-books of anatomy in general use the macroscopic appearance of the disc is described in very general terms.

A few only of the foregoing descriptions apply to discs of known ages. In most of the accounts given, no reference is made to the age of the specimen described. To obtain a comprehensive idea of the changes occurring in the tissue components of the disc, a wide range of specimens of known ages is required for examination.

The structure of the disc at a few known ages is given by Smith (1931), Keyes & Compère (1932), and more detailed descriptions of the structure of the lumbosacral disc in the various decades are given by Coventry, Ghormley & Kernohan (1945). Amprino & Bairati (1934), in their studies of age changes in fibrocartilage, employed the intervertebral discs as one of the subjects for study, and Franceschini (1947) has investigated the changes in the arrangement of the fibres of the annulus fibrosus at different ages, by examination with polarized light.

The present investigation was undertaken, following a previous study of the prenatal changes in structure of the developing intervertebral disc, to provide data for a survey of the life history of the disc. Attention was particularly directed to the changes occurring in the nucleus pulposus.

MATERIALS

Thirty fresh post-mortem specimens of lumbar discs were obtained from subjects of known ages, ranging from full term to 80 years of age, and, as far as known, free from spinal disease or deformity. The specimens were examined macroscopically and microscopically. For microscopic examination serial sections of some complete discs were made; in other discs, a strip was taken from the middle of the disc in the sagittal plane, thus including the nucleus pulposus, and then serially sectioned. Some specimens obtained by operation from patients with protrusion of the lumbar discs were also examined for comparison.

DESCRIPTION OF SPECIMENS

The specimens described are selected as showing well-marked stages of the structural changes in the tissue components of the disc. The marked pathological changes (haemorrhage, pigmentation) occurring with increasing frequency, in ageing discs, are not considered.

At full term

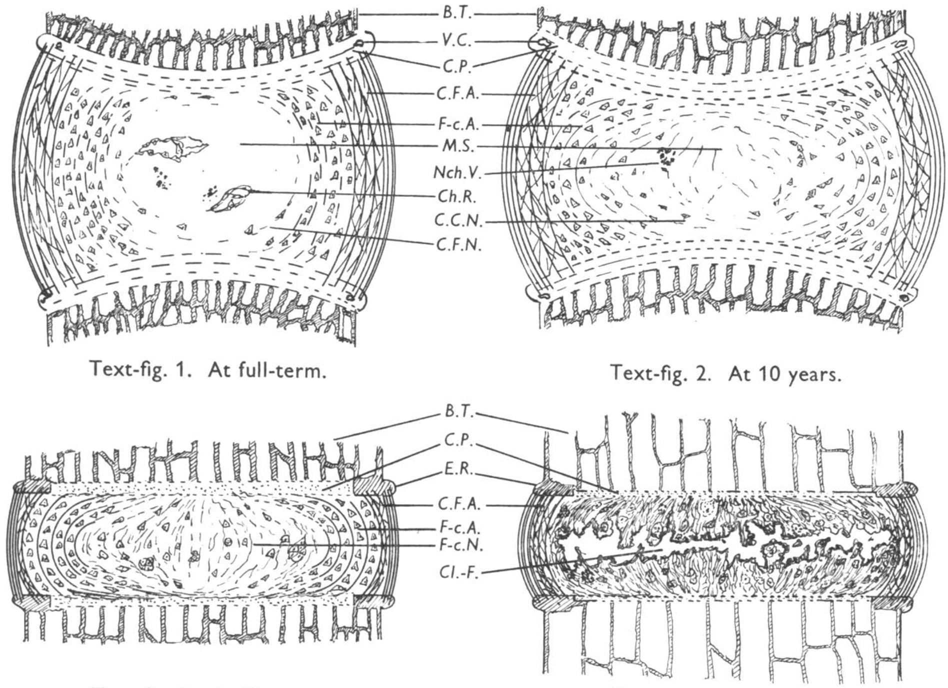
In the photograph, two vertebrae with the intervening disc are seen (Pl. 1, fig. 1; Text-fig. 1). The cartilage plates capping the end-surfaces of the vertebral bodies are clearly defined, and in the disc, the inner nucleus pulposus and the outer annulus fibrosus are seen. The disc, as a whole, is biconvex and of considerable thickness, the vertical height being almost half that of the adjacent vertebral bodies. A noteworthy feature is the size of the nucleus pulposus, which occupies in this plane half the antero-posterior diameter of the whole disc. The shape of the nucleus pulposus is quadrilateral, and it appears to be composed of an apparently homogeneous substance containing scattered clumps of cells. The annulus fibrosus exhibits an outer area of densely aggregated fibres and a less dense area, between the former area and the nucleus pulposus. In both these areas, arching fibres may be seen, which, at their terminations, enter the cartilage plates.

On microscopic examination the periphery of the annulus shows a dense aggregation of collagenous fibres, which run across the intervertebral space, following an outwardly convex course. The terminations of the fibres are lost in the matrix of the cartilage plates, to which they are firmly anchored. Apart from the most peripherally situated lamellae, these fibres do not follow a simple course, but splitting of some fibre-bundles occurs with subsequent joining with those of other bundles; some fibres pursue a spiral course across the intervertebral space, and the interlocking and crossing of the fibres forms an intricate system (Pl. 1, fig. 2).

Within this area of the annulus is the less dense area previously referred to. This is a zone of fibrocartilage, the fibres of which follow an arching, outwardly convex course. Within this zone again is the nucleus pulposus, the distinction between the two areas being clearly demarcated. There is, however, a narrow transitional zone.

The nucleus pulposus is formed by a mass of homogeneous, mucoid substance, in which are seen at intervals the remains of a chorda-reticulum (Pl. 1, fig. 3). The chorda-reticulum is formed by a meshwork of notochordal cells, separated by intercellular spaces containing mucoid substance, some cells being compressed into long tracts, others being isolated as small clumps. Typical notochordal cells are recognizable, but many cells show nuclear pyknosis and fragmentation. This area may be termed the 'notochordal' area.

The narrow transitional area referred to above exhibits the following features. The innermost area of the fibrocartilaginous component of the disc appears to be undergoing liquefactive changes, resulting in the separation of cartilage cells and fibres from this area and their mingling with the mucoid substance at the periphery



Text-fig. 1. At full-term.

Text-fig. 2. At 10 years.

Text-fig. 3. At 33 years.

Text-fig. 4. At 80 years.

Text-figs. 1–4. Diagrammatic representation of age changes in the tissues of the disc.

List of Abbreviations

B.T.	**Bone trabeculae**	***E.R.***	**Epiphyseal ring**
C.C.N.	**Cartilage cells in the nucleus pulposus**	***F-c.A.***	**Fibrocartilage of annulus fibrosus**
C.F.A.	**Collagenous fibres of annulus fibrosus**	***F-c.N.***	**Fibrocartilage of nucleus pulposus**
C.F.N.	**Collagenous fibres in the nucleus pulposus**	***M.S.***	**Mucoid substance**
Ch.R.	**Chorda-reticulum**	***Nch.V.***	**Notochordal vestige**
Cl.F.	**Cleft-formation**	***V.C.***	**Vascular canal**

of the 'notochordal' area. Similar changes, though much less obvious, appear to be occurring at the faces of the cartilage plates bounding the nucleus pulposus above and below. Centrally the intervertebral surfaces of these plates seem to be well defined, but, more peripherally, fibres running parallel to the surface of the plate arch to mingle with those of the fibrocartilaginous component.

Small blood vessels are present between the lamellae of the annulus fibrosus in the postero-lateral regions of the disc, but the nucleus pulposus is avascular.

In specimens of the ages of 3, 17 and 21 days the structural features are as described at full term.

At 5 *weeks*

The general features are much the same as at birth (Pl. 1, fig. 4), the components of the disc from without inwards being, the zone of collagenous fibres, the fibrocartilaginous area, the transitional area and the 'notochordal' area.

The nucleus pulposus occupies a large area relative to the total area of the whole disc, but the thickness of the disc compared to the height of a vertebral body is less than in the previous stages. There is an alteration in the shape of the nucleus pulposus, which has now assumed a more oval form as seen in the median sagittal plane.

A fairly sharp demarcation exists between the nucleus pulposus and the surrounding fibrocartilage, the transitional area being very narrow. This latter area again shows merging of the tissue components of the inner aspect of the fibrocartilaginous area with the 'notochordal' element. In the more central parts of the 'notochordal' area, mucoid substance containing small clumps of notochordal cells is present, many of these cells showing signs of degeneration. The nucleus pulposus is avascular.

Similar conditions are present at 5 months of age.

At 4 *years*

On macroscopic examination, the annulus fibrosus and nucleus pulposus are clearly defined, and the latter occupies a considerable part of the total area of the whole disc.

On microscopic examination the outer collagenous fibres, the fibrocartilaginous zone, the transitional area and the 'notochordal' area are seen, but this latter area shows further changes. There is abundant mucoid substance in this area which now contains a loose irregular network of fine collagen fibres. At intervals in the notochordal area, remains of a chorda-reticulum are present and isolated clumps of notochordal cells, many of which are degenerated (Pl. 1, fig. 5). More cartilage cells are seen in the peripheral area of the nucleus pulposus. The nucleus pulposus remains avascular.

At 10 *years*

Microscopically the same tissue components as previously described are present. The nucleus pulposus is still relatively very large and occupies about half the area of the disc. In this area abundant mucoid substance is present, more collagenous fibres are present and small groups of cartilage cells are seen scattered in the mucoid substance (Pl. 1, fig. 6; Text-fig. 2). Remains of a chorda-reticulum are still present, but most of the cells are degenerated and very few typical notochordal cells are recognizable.

No blood vessels enter the nucleus pulposus.

At 21 *years*

Macroscopically, the annulus and the nucleus pulposus are clearly demarcated, but the distinction is not so pronounced as in the previous stages. The tissue of the nucleus appears less translucent, and though it is of markedly gelatinous character, it is of firmer consistency.

Microscopically, the tissue zones previously described can be recognized, but the innermost zone can no longer be described as 'notochordal'. This area is now occupied by a delicate, irregularly arranged fibrocartilaginous network containing much mucoid substance. The cartilage cells are scattered through this tissue sometimes singly or in small groups, but occasional nests of cells are present (Pl. 2, fig. 7). The nucleus pulposus is avascular.

At 33 years

With the naked eye annulus and nucleus pulposus can be defined, but the distinction is less well-defined than in earlier stages. The nucleus has lost its translucent appearance, and appears whitish, is of firmer consistency and may be described as fibrogelatinous.

On microscopic examination the fibres of the annulus have become coarser and somewhat hyalinized. In the nucleus the fibrocartilage network shows coarser fibres and cartilage cells are more numerous. The cells are scattered or present in small groups and more nests of cells appear (Pl. 2, fig. 8; Text-fig. 3). Mucoid substance is still present in the matrix, but the whole tissue appears to have lost fluid and to have become denser. The nucleus pulposus remains avascular.

At 40 years

The annulus fibrosus and the nucleus pulposus can still be distinguished, though the demarcation is becoming progressively less obvious. The nucleus pulposus appears whitish and is of firm consistence.

Microscopically, there is little change in the annulus fibrosus, but the nucleus pulposus again shows irregularly arranged fibre bundles and numerous cartilage cells (Pl. 2, fig. 9), nests of cartilage cells being more numerous. The whole fibre meshwork appears denser and shows evidence of loss of fluid. No vessels enter the nucleus.

At 50 years

There is little change in the general appearance of the disc. Annulus fibrosus and nucleus pulposus can still be distinguished. Microscopically, the fibres of the annulus show hyalinization and coarsening. The tissue of the nucleus pulposus is now a fibrocartilage and very like the surrounding tissue, but the fibre bundles are less closely aggregated and there is no comparable fibre architecture, the bundles of fibres coursing indiscriminately. Numerous cartilage cells are present and nests of cartilage cells are frequently seen (Pl. 2, fig. 10). No vascularization of the nucleus pulposus is seen.

At 64 years

The distinction between the nucleus pulposus and the annulus fibrosus is not very clear macroscopically. Microscopically, hyalinization of the fibres of the annulus is present, but there is still evidence of a definite fibre architecture. The nucleus pulposus is composed of a dense fibrocartilage which shows the characteristics described for the previous stage (Pl. 2, fig. 11). Masses of amorphous substance are found at places between the fibre bundles. The nucleus pulposus is avascular.

At 75 years

Macroscopically, distinction between the nucleus pulposus and the surrounding tissues is difficult, but the nucleus still has a softer consistency than the perinuclear components. In the low-power photograph, cleft formation is seen in the disc, horizontal fissuring extending almost completely through the disc (Pl. 2, fig. 12).

Microscopically, there is little change in the tissues surrounding the nucleus pulposus. The nucleus itself is a coarse fibrocartilage (Pl. 3, fig. 13) and is avascular.

At 80 years

On macroscopic examination, conditions are much as those described in the 75-year-old stage. The whole intervertebral mass appears as a uniform plate of tissue, and distinction between the nucleus pulposus and the annulus fibrosus is lost. Cleft formation is again seen in the disc (Pl. 3, fig. 14; Text-fig. 4).

Microscopically, the peripheral layers of collagen fibres are still seen arching, with outward convexity, between the adjacent vertebrae. These fibres are hyalinized, the sharp definition of their structure being lost. Within these, the fibrocartilaginous component of the disc is seen, the component fibres are hyalinized, and the cartilage cells appear indistinct, but fibres can be traced into the thin cartilage plate covering the upper and lower surfaces of the vertebrae. Where the terminations of these fibres merge with the matrix of this cartilage a very narrow transitional zone is occasionally recognizable. Towards the periphery, at the outer borders of the vertebrae, the cartilage plates appear to be absent and the fibre terminations enter the bone directly.

More centrally in the disc, the area of the nucleus pulposus can still be recognized by the indiscriminate course of the fibre bundles and by their less close aggregation. Numerous cartilage cells are present between the fibre bundles and nests of these cells are of frequent occurrence. The fibre bundles show lack of definition and appear hyalinized like those of the perinuclear components (Pl. 3, fig. 15). The nucleus is avascular.

Cleft formation in the disc is a marked feature, both horizontal and vertical clefts being present. The horizontal cleft formation passes almost completely through the disc from the anterior to the posterior surface, but some fibres are present in this outer region, and beyond these are the fibres of the longitudinal ligaments. The vertical clefts in some instances result in the appearance of processes resembling villi.

Specimens obtained by operation

Specimens obtained from patients with disc lesions between 20 and 40 years of age, examined microscopically, show structural features similar to those described above. They contain tissue from the nucleus pulposus showing delicate fibrocartilage containing mucoid substance and exhibiting nesting of cartilage cells, and fibre aggregations from the outer annulus components. Occasionally parts of the cartilage plates and fragments of the bone of the vertebra are seen.

It may be remarked that considerable individual variation occurs in the structure of the intervertebral disc, in the sense that some discs appear to have aged more quickly than others. This is in accordance with the known individual variability of age changes in the body generally.

Review of observations and discussion

(1) *The tissue-components of the intervertebral disc*

The descriptions of the constitution of the intervertebral disc, as usually given, require consideration. The disc is commonly described as consisting of two components, an outer firm annulus fibrosus, and an inner soft nucleus pulposus. To these components, some authors add the cartilage plates, which, capping the end-surfaces of the vertebral bodies, bound the intervertebral area cranially and caudally. In this connexion, it may be noted that in early stages of development, the tissue intervening between the developing cartilaginous vertebral bodies is frequently referred to as the 'perichordal disc' (Dawes, 1930; Wyburn, 1944). This perichordal disc presents three areas, a cranial, a middle, and a caudal area. The middle component of dense mesenchyme is the *anlage* of the intervertebral disc, while extension of chondrification of the vertebral bodies invades the less dense cranial and caudal mesenchymal areas, which are the primordia of the cartilage plates. Thus, some authors (Prader, 1947) consider the cartilage plates as parts of the vertebral bodies, while others regard them as parts of the disc. In the present description they are considered as 'vertebral' and referred to only as far as they are concerned in the anchoring of the disc fibres, attention being primarily directed to the soft tissues.

The description of the disc as comprising an annulus fibrosus and a nucleus pulposus is somewhat simplified. From the observations in the present investigation, it is seen that, traced horizontally from the periphery of the disc towards the centre, the tissue-components are (1) the narrow outermost zone of collagenous fibres, within this (2) the wider zone of fibrocartilage, followed by (3) a transitional area between the latter, and (4) the nucleus pulposus. The transitional area varies with age. In the earlier periods it is narrow and separates tissues with very different structural features, so that the distinction between annulus and nucleus is very obvious. Later, with the subsequent transformation of the structure of the nucleus pulposus and the merging of this tissue with that of the perinuclear tissue, the transitional area is difficult to define.

If the terms in common use are to be retained, the disc may be described as consisting of an outer annulus fibrosus, and an inner nucleus pulposus. The annulus fibrosus exhibits a narrow peripheral zone of collagenous fibres and an inner zone of fibrocartilage. The structure of the nucleus pulposus varies markedly with the advance of age. The various components of the disc may be considered separately.

(2) *The annulus fibrosus*

(*a*) *The outer collagenous component.* The course of these fibres at the periphery of the disc may be traced by simple dissection, and the obliquity of the course of many superficial fibres and the crossing with fibres running in the opposite direction, clearly demonstrated. In the lumbar region, fibres arising from the postero-lateral region of the discs may be shown to pass caudally and laterally, where they fan out to reach and become attached to the pedicles of the next subjacent vertebra. These fibres thus form the anterior, and, in part, the inferior boundary of the outer opening of the intervertebral canal. Other fibres may be traced from this area of the disc, passing caudally and anteriorly to join the periosteum of the subjacent vertebra near its lower border, or to blend with those of the subjacent disc, crossing in this course the lumbar vessels. Fasciculi are frequently seen passing between the lumbar arteries and veins.

In a sagittal section of the disc, examined microscopically, these oblique fibres are sectioned transversely at various angles, while a series of vertically running fibres is sectioned longitudinally. Deep and superficial, obliquely running fibres, intersecting the vertical fibres, may be observed. The vertical fibres show an arched course with an outward convexity, are closely aggregated and mingle with the fibres of the longitudinal ligaments, the connexion being more intimate anteriorly. With the advance of age, all the collagenous fibres undergo hyalinization but show no further changes.

(*b*) *The fibrocartilaginous component.* This is the principal component of the annulus fibrosus, and in it the fibre architecture is of an intricate character. Concentric and vertical systems of fibres are present, and the splitting and joining of adjacent fibre bundles result in a complicated meshwork. On macroscopic examination the upper or lower surface of a disc presents somewhat the appearance of damask, the patterns running concentrically. Fick (1904) refers to this and states that the earlier authors thought that the pattern and slight differences in colour observed represented different component tissues. Henle (1872) was apparently the first investigator to point out that only one tissue was concerned and that these phenomena were due to the differing courses of the fibres, causing an unequal reflexion of incident light.

Übermuth (1929, 1930) considers that the formation of the fibrocartilage component occurs only with the advent of mechanical stresses associated with the sitting up of the infant at 6 months after birth and with walking, and regards it as an age change. Böhmig (1930) associates the formation of this component with the presence of vascularization. In referring to vessels which he states are present in the disc, he states: 'Die sind es ferner, die die Fasern des Annulus lamellosus zu bilden und liefern scheinen und dessen verflochtene Fasersysteme entstehen lassen', and refers to a development of the fibres from the vessels of the disc thus: 'Diese Fasern scheinen von allen Baudscheibe-Gefässen, besonders aber den axialen, auszugehen, wodurch die eigentümliche Verlaufsrichtung der Fasersysteme des späteren Annulus lamellosus ihre Erklärung findet.' It has, however, been shown (Peacock, 1951) that very early in development (at 10 mm. C.R.) orientation of the mesenchymal cells occurs, that peripheral fibres develop by the 29 mm. stage, and that the fibrocartilaginous component is derived from a specialized embryonic cartilage directly surrounding the notochord. Further, these processes occur before vessels are present in the disc and the complex fibre architecture develops before any mechanical stresses are encountered.

The principal age changes occurring in this component are closer aggregation of the fibres during the second decade, and with the third decade the onset of coarsening and hyalinization of the fibres, nesting of the cartilage cells, some of which begin to show signs of degeneration, desiccation and cleft formation. From this period on, such changes are slowly progressive.

The disc participates in the general growth processes occurring in the body and in this connexion attention may be directed to the mode of termination of the fibres in the cartilage plates. The ends of the fibres are lost in the matrix of the cartilage of the plates (Pl. 3, fig. 16). This area is especially referred to by Kaufmann (1854) and Amprino & Bairati (1934), the latter authors designating it as a transitional zone and pointing out that during the active growth of the disc this area is a prominent structural feature. The fibrocartilaginous area increases at the expense of the cartilage of the plates. Coventry *et al.* (1945) note that after the age of 14 to 16 years proliferative processes in the plate are much less active, and that by the age of 20 years there is little evidence of endochondral growth. With the extension of ossification of the vertebral body, the cartilage plates become very thin, and coincidently with this, growth in thickness ceases in the intervertebral disc.

In the adult, the outermost circumferential fibres of the annulus are embedded in the so-called 'epiphyseal ring', which is developed from the cartilage plate. The method of its development may be briefly described. Frazer (1940) refers to ossification taking place in the periphery of the cartilage plate. Schmorl (1928*b*, *c*), in describing the special characteristics of juvenile vertebrae, gives a much more detailed account. Macerated juvenile vertebral bodies exhibit radially arranged furrows on the cranial and caudal vertebral end-surfaces, which, deepening as they approach the periphery, notch the borders of the vertebral bodies. Prior to maceration, these furrows are occupied by corresponding processes arising from the apposed surfaces of the cartilage plates. In the peripheral areas of these cartilaginous processes, small centres of ossification appear from as early as 8 years of age, and thus a peripheral ring of small centres of ossification develops. Later, these centres coalesce to form the 'epiphyseal ring', which finally fuses with the vertebral end-surface, with the cessation of growth. Even after complete fusion, persistent juvenile furrowing may occasionally be seen on the end-surfaces of adult vertebrae, within the epiphyseal rings. Schmorl considers that these epiphyseal rings serve a special function, in acting as an anchoring mechanism for the outer fibres of the annulus. These rings are indicated in Text-figs. 3 and 4.

As regards the growth of the disc, in girth, it may be noted that in the first decade, the nucleus pulposus is almost centrally placed. Later, the nucleus appears to approach the posterior aspect of the disc. This is due to the fact that the disc and vertebral body do not increase in girth concentrically, the increase taking place by apposition, on the anterior aspect of these structures. The growth of the disc in the thoracic and lumbar regions follows that of the vertebral bodies, the mode of growth of which has been shown radiologically by Knutsson (1948).

In connexion with the growth processes occurring in the disc, it may be noted that the discs of the cervical region show certain special features. Whereas the thoracic and the lumbar discs throughout prenatal and postnatal life occupy the whole area of the vertebral end-surface, the cervical discs in prenatal and early postnatal life are confined to the area of the true centrum of the vertebral body. This centrum is clearly demarcated from the vertebral-arch component of the vertebral body by the cartilage of the neurocentral synchondrosis. Bony fusion begins 3 or 4 years after birth, though evidence of the line of union remains for some years after this. Information regarding the peculiarities of the lateral areas of the cervical discs has accumulated as a result of studies directed to the so-called Luschka's, neurocentral or unco-vertebral joints present in the cervical vertebral column. Luschka (1858), in describing the connexions of the cervical vertebrae, states that (excluding the atlas and axis) three joints (a middle and two lateral) are present, between the end-surfaces of the cervical vertebrae. The lateral joints possess a clearly defined cavity, well demarcated from the intervertebral disc. He states that these cavities may be occupied by connective tissue, a condition regularly found in the newborn, but that in later years, as a result of fissuring in the nucleus pulposus and annulus fibrosus, connexion may occur between the lateral joints and such fissures. He refers to the fact that the annulus does not encircle the whole vertebral connexion, but extends laterally on the vertebral body to be limited by the medial limit of the lateral joint. He refers to the presence of synovial fluid and villiform processes of connective tissue, in the cavities of the lateral joints. Many authorities have since assumed that these joints are synovial and they are often described as such. Rathcke (1934) reports that he does not find true joint cavities present, but interprets these formations as tears in the disc. His Fig. 1, of a disc of a newborn child illustrated by Rathcke, clearly shows the extent of the disc in the horizontal plane; in Fig. 2 the lateral extension, together with cleft formation, is seen in a specimen from a 20-year-old man. Krogdahl & Torgersen (1940) find crevices laterally placed in the cervical region, in the sites described by Luschka. They consider the medial boundary to be formed by the disc, but question the propriety of designating these formations as true joints. Töndury (1943) has made investigations employing a much wider range of material, both prenatal and postnatal, and finds that at birth and up till 7 years of age, the disc is confined to the centrum of the vertebra. At 9 years he finds a further lateral extension of the disc, beyond the centrum into the region of the uncinate processes or neurocentral lips. At the same time a cleft appears, present on both sides, which contains connective tissue including blood vessels and fat. The process of cleft formation is brought about by loosening, degeneration and rupture of the fibres in the lateral part of the annulus. This process is a regular feature in the cervical region, and the clefts present are the so-called Luschka's joints, though no joint space, in the sense of a synovial cavity, is present. Töndury considers this phenomenon of cleft formation to be the result of functional demands associated with the mobility of the cervical column. He has shown, in the case of a 24-year-old man, that the lateral clefts may extend to the nucleus pulposus, so that the disc is subdivided horizontally, very much as is seen in the 80-year-old specimen of a lumbar disc in this investigation.

The direction of certain of the fibre components of this fibrocartilaginous area are worthy of comment (Pl. 3, fig. 17). At the superior and inferior boundaries of the nucleus pulposus, at the opposing vertebral end-surfaces, as seen in the median sagittal plane, there are to be observed fibre bundles which run almost parallel to the surface of the vertebra, but which, as they reach the anterior of the posterior aspect of the nucleus pulposus, turn towards the opposite vertebra and mingle with the outwardly convex and vertically running fibres in the perinuclear area of the fibrocartilaginous component. These fibres are at first closely aggregated near the vertebrae. As they pursue their outward course, however, they become separated by mucoid substance continuous with that of the nucleus, and they and their accompanying cartilage cells merge with the tissue of the nucleus. This is a transitional zone between the cartilage plate of the vertebral body and the nucleus pulposus, but is less pronounced than the transitional area described below. With the advance of age and the transformation of the nucleus, these originally horizontally running fibres change their course and come to run almost vertically into the nucleus.

Other age changes, reflected in the course of the fibres, are referred to by Franceschini (1947, 1949). He examined specimens of discs from the cervical, thoracic and lumbar regions, at various ages, by polarized light. He states that in horizontal sections, all regions show the characteristic concentric arrangement of fibres, which remains fundamentally unchanged with the advance of age, but that birefringence, slight at 3–5 years, is accentuated at 13–15 years. As seen in frontal and sagittal sections the fibre orientation at 7–10 years in the cervical region is that of a series of superimposed parallelepipeds enclosing the nucleus pulposus, while in the dorsal and lumbar regions the orientation may be compared to that of an ovoid with a transversely placed major axis. This architecture changes with age, and frontal and sagittal sections in specimens of 18–20 years show that the major lamellae near the nucleus pulposus assume a complex configuration which he designates as 'a cuscinetto'. The vertical peripheral lamellae are succeeded by more internally situated lamellae arching with an inwardly directed concavity. These are succeeded by central lamellae, some vertical, some undulating, and finally next to the nucleus pulposus, there are other lamellae, arched but with the concavity facing outwards. This architecture appears early at 18–20 years in the lumbosacral region and later in the dorsal and cervical regions. With further advance of age the lamellar complex undergoes many variations, in response to mechanical demands. At 40–45 years he reports marked lateral projection of the outwardly arching lamellae, which he considers an anatomical basis for discal herniation. In the series investigated no regular pattern could be ascribed to the fibres of the transitional area between nucleus and annulus.

(3) *The transitional areas*

Two transitional areas have been previously referred to, one associated with the terminations of the fibres of the fibrocartilaginous component in the cartilage plates (Pl. 3, fig. 16), the other situated at the junctional area of the nucleus pulposus and the cartilage plates (Pl. 3, fig. 17). This latter area is similar in structural principle to that to be described, but is less evident.

The area now referred to is that seen at the periphery of the nucleus pulposus, between this and the fibrocartilaginous component of the annulus, and the structural features are shown in Pl. 3, fig. 18.

It may be defined as the area of the merging of the tissue of the 'notochordal' nucleus pulposus and the inner part of the fibrocartilaginous component. In this area of the fibrocartilaginous zone, a process of liquefaction of the matrix appears to be taking place, resulting in the separation of the fibres and cartilage cells which are seen passing into the periphery of the nucleus pulposus. Luschka reports strands of tissue derived from the perinuclear area projecting into the notochordal area, and compares them with 'synovial villi' as seen in the cavity of a synovial joint. The comparison is rather misleading, as the structure and formation of the structures concerned are different.

The tissue changes occurring in this region appear to be the first stages in the transformation of the nucleus pulposus, and have begun at birth. Thereafter they are progressive and, as the transformation of the nucleus is accomplished, the transitional zone becomes more difficult of definition.

(4) *The nucleus pulposus*

The structure of the nucleus pulposus has been a subject of controversy, the principal argument concerning the fate of the notochord and the part this structure plays in the formation of the nucleus pulposus.

There is an extensive earlier literature on this subject, which was summarized by Williams (1908). It is sufficient for the present purpose to state that two theories were held, one maintaining that the notochord degenerated and disappeared without trace, the other that it played a part of more or less significance in the formation of the nucleus pulposus.

From observations made in the present investigation, it may be concluded that a notochordal element is definitely present in the early postnatal stages, that this progressively diminishes in extent, and is progressively replaced by fibrocartilage with the advance of age.

The difficulty of definition of the structure of the nucleus pulposus arose from the fact that the earlier observers did not examine a sufficiently wide range of specimens of known ages, to show that transformation of the nucleus was taking place. Hence, their descriptions, in the main correct for the specimens examined, could not give an adequate picture of the changing structural features.

The latest age periods at which notochordal elements are present in the nucleus have been variously estimated by different authors. In fact, there are very few references to definite age periods recorded, the age period being referred to in general terms such as 'adult' or by decades. Schaffer (1910) stated that in a 30-year-old man, he could recognize no characteristic notochordal tissue, other than detritus, which he considered to represent the final vestiges of the epithelial chorda-cells of the newborn. In a later contribution (1930) this investigator figures and describes the nucleus pulposus in the newborn and from subjects of 19 and 28 years of age. In the 28-year-old subject, he states that 'of chorda-tissue, only granular detritus and large, homogeneous oxyphil scales are present, often joined into rounded masses by mucoid, while the surrounding cartilage of the disc shows softening, whereby whole territories of cartilage cells are isolated and may enter the chorda-cavity'. He concludes that, ultimately, in the adult nucleus pulposus the intimate mingling of products of degeneration of notochordal tissue, and of the surrounding cartilage, renders impossible the determination of the origin of individual cells and cell remains. Yet he states that in the nucleus of a subject of 67 years, he can recognize remains of chorda-cells, but considers that 'isogeneous encapsulated cell-groups are derived from cartilage', as Dursy (1869) had previously maintained. Keyes & Compère (1932) state that in a 4-year-old child, 'notochordal cells are difficult to find', while Amprino & Bairati (1934) suggest that after 15 years of age conspicuous masses of notochordal cells are no longer present, but that small groups may be found on careful examination. Coventry *et al.* (1945) report that they did not find typical notochordal cells in the specimen of 10 months of age. In the present series, remains of a chorda-reticulum and but few recognizable isolated chorda-cells are to be seen in the specimen of the 10-year-old subject, and after this age no chorda-vestiges are present.

Some difficulty has arisen over the identification of grouped cells. The older authors (Kölliker, 1879; Fick, 1904) refer to the presence of notochordal cells in 'adults', no specific age being given, and refer also to 'mother cells' which they assume to be of notochordal origin. Schaffer (1930) suggests an origin for these cells, as noted above, and Petersen (1930) has never found notochordal cells present in the adult and considers the presence of such cells to be 'very doubtful'. He considers that the vesicular cells described and illustrated by Fick (1904), and the older authors, are nests of cartilage cells with capsules. It has been pointed out by Amprino & Bairati (1934) that these structures must have originated from cartilaginous elements, for they are evidently late in making an appearance, and further these authors have observed similar cell groups in the symphysis pubis, in which, of course, no notochordal elements are ever present. From observations in the present investigation, it appears that the nested cells are cartilage cells.

Some further aspects of the question of persistence of notochordal tissue require consideration. Musgrove (1891) refers to the presence of notochordal tissue in an adult subject, connecting the nuclei pulposi above and below the 4th lumbar vertebra, by passing through the body of this vertebra. The condition was discovered fortuitously. The microscopic findings reported are not very convincing, and there is some doubt as to whether true notochordal tissue was present. Schmorl (1928*a*), from an investigation of 3000 vertebral columns, reports the presence of 'Chordareste' as frequent, and that these may be present in the bodies of the vertebrae. He states that true notochordal cells were observed microscopically.

In examining a range of serially sectioned human embryos, abnormalities of the notochord are not uncommonly observed. Branching of notochordal tissue from the main notochordal column with protrusions extending in variable directions, both into the intervertebral discs and into the vertebral bodies, may be observed. Fragmentation of the notochord may be present, with the detachment of small islands of notochordal tissue, and their location in the discs or vertebral bodies. Partial duplication of the notochord has been described by Johnston (1931).

Such embryonic 'rests' may provide the basis for the development of chordomata. Spheno-occipital and sacro-coccygeal chordomata are well-known clinical and pathological entities. Chordomata affecting the cervical, thoracic and lumbar vertebrae are less common, but Cappell (1928), Davis & Weil (1928), Machulko-Horbatzewitsch & Rochlin (1930), Mabrey (1935), Faust, Gilmore & Mudgett (1944), and Morris & Rabinovitch (1947) all record such cases. Excluding sacro-coccygeal chordomata, vertebral chordomata are mainly found in the cervical region (Adson, Kernohan & Woltman, 1935), while lumbar chordomata are next in frequency.

Hence, embryonic notochordal tissue may persist in certain instances, and may either remain quiescent or develop neoplastic characteristics. In the normal course of events, the fate of the notochordal cells appears to be one of progressive diminution in number associated with retrograde changes and final disappearance.

The nucleus pulposus has considerable power of imbibition of fluids, far in excess of that of the annulus fibrosus. With advancing age, desiccation of the disc is progressive. Investigations of the water content of the disc at various ages, by Püschel (1930), Keyes & Compère (1932), and Schümmelfeder & Schümmelfeder (1949) show very similar results. Püschel finds the highest values for the newborn, both for the annulus (77 %) and the nucleus (88 %). At 18 years, the values are 72 and 80 % respectively. In the third decade, the annulus reaches a value of 70 % which it retains till old age, when it decreases slightly, the nucleus, however, undergoing a steady decrease. Thus, the difference between annulus and nucleus progressively decreases. At 77 years, Püschel finds the value for the annulus to be 67 % and for the nucleus 69 %. The changes are closely paralleled by the structural changes occurring at the corresponding age periods, as observed both macro- and microscopically. The decrease in height of the discs resulting from the loss of volume is shown by the measurements of Jacobi (1927), and from comparisons of such measurements in the newborn and adult given by Hasselwander (1938). The desiccation occurring in the disc probably plays an important part in the cleft formation seen at later ages. In relationship to the fluid content of the disc, it appears that the disc exhibits its greatest elasticity and power of resistance to pressure, towards the end of the 2nd and during the 3rd decade.

In reviewing the life history of the disc, it is worthy of note that the annulus fibrosus undergoes comparatively little change, while the nucleus pulposus exhibits continual structural changes from the time of its inception, throughout life. A consideration of these tissue changes, in relation to the clinical conditions of 'protrusion of the disc' or 'herniation of the nucleus pulposus', suggests that with gradual transformation of the disc into a uniform plate of fibrocartilage true herniation of the nucleus pulposus would become less frequent with advancing age.

Vascularization of the disc

In the literature, the accounts of the blood supply of the disc vary, and such variation depends on whether the cartilage plates are included in the designation 'disc' or not.

Keyes & Compère (1932) describe the adult disc as being avascular. Übermuth (1929, 1930) and Coventry *et al.* (1945) describe the vessels as being limited to the cartilage plates and as persisting up to 20 years of age. Luschka (1856) and Fick (1904) refer to vessels in the annulus only, and Brack (1929) describes vessels in the outer part of the annulus and blood islands as present in the cartilage plates in the earlier years of life. Böhmig (1930) gives an account of an elaborate blood supply furnished by two dorsal, ventral and axial vessels, and suggests that these supply the cartilage plates, annulus and nucleus. His illustrations certainly show the vessels in the cartilage plates, but they are apparently not present in the annulus and nucleus. The 'pinselartigen' branching which he describes for the disc vessels, are regarded by Schaffer (1910) as artefacts. Böhmig considers that these vessels persist till 25 years of age. Smith (1931) states that 'nutritive channels' are present in both annulus and nucleus of young, healthy discs. Those in the nucleus have a thin wall 'in which endothelial cells were not made out' but in the annulus, the channels, which could be traced into the cartilage plates, were lined with a single layer of flattened cells. Numerous leucocytes are present in the vessels in the annulus and nucleus, but red cells, absent in these two components, are present in the channels in the cartilage plates.

From the present investigation, it is concluded that, as far as the soft tissues are concerned, small blood vessels are present, running mainly concentrically among the lamellae in the postero-lateral aspects of the annulus, but that the nucleus pulposus remains avascular throughout life.

SUMMARY

1. Descriptions are given of the tissue changes taking place in the structural components of the human intervertebral disc, from birth to 80 years of age.

2. The disc is composed of a peripheral, firm annulus fibrosus comprising an outer zone of collagenous fibres, and an inner zone of fibrocartilage, and a central, soft nucleus pulposus. The fibre architecture of the annulus is intricate, and is present at birth. The nucleus pulposus, at birth, is formed mainly by modified notochordal tissue.

3. With the advance of age, the fibres in the annulus become coarsened and hyalinized, while in the nucleus, the notochordal element is replaced by fibrocartilage. Notochordal tissue appears to be absent after 10 years of age. The fibrocartilage of the nucleus, at first delicate and containing much fluid, becomes progressively coarsened and desiccated. Desiccation occurs in the disc as a whole, especially after 30 years of age, but is more marked in the nucleus than in the annulus. In advanced age, macroscopic distinction between nucleus and annulus is lost.

4. Transformation of the nucleus pulposus appears to result from addition to, and replacement of, the notochordal tissue by fibres and cartilage cells derived from the inner part of the fibrocartilaginous zone by a process of liquefaction.

5. The ultimate transformation of the intervertebral disc into a uniform plate of fibrocartilage, suggests that the incidence of true herniation of the nucleus pulposus would diminish with advancing age.

6. Small blood vessels are present, running concentrically among the lamellae in the postero-lateral regions of the annulus fibrosus, but the nucleus pulposus remains avascular throughout life.

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EXPLANATION OF PLATES

Plate 1

Fig. 1. Full-term intervertebral disc. Lumbar region. Median sagittal section showing notochordal area (*N.*), fibrocartilage zone (*F-c.*), zone of collagenous fibres (*C.F.*). Haematoxylin and eosin. ×8·4.

Fig. 2. Full-term intervertebral disc. Lumbar region. Sagittal section of periphery of annulus fibrosus showing crossing of fibres. Masson's trichrome. ×100.

Fig. 3. Full-term intervertebral disc. Lumbar region. Median sagittal section through notochordal area, showing remains of chorda reticulum and mucoid substance. Haematoxylin and eosin. ×135.

Fig. 4. Postnatal disc, 5 weeks. Lumbar region. Median sagittal section through nucleus pulposus and surrounding fibrocartilage, showing groups of notochordal cells (*N.*), mucoid substance in nucleus pulposus, liquefactive changes in surrounding fibrocartilage (*F-c.*). (Transitional areas.) Masson's trichrome. ×100.

Fig. 5. Postnatal disc, 4 years. Lumbar region. Median sagittal section of nucleus pulposus showing degenerated notochordal cells (*N.*) and delicate fibres. Masson's trichrome. ×100.

Fig. 6. Postnatal disc, 10 years. Lumbar region. Median sagittal section of nucleus pulposus showing groups of cartilage cells (*c.*) and mucoid substance (*M.S.*). Masson's trichrome. ×100.

Plate 2

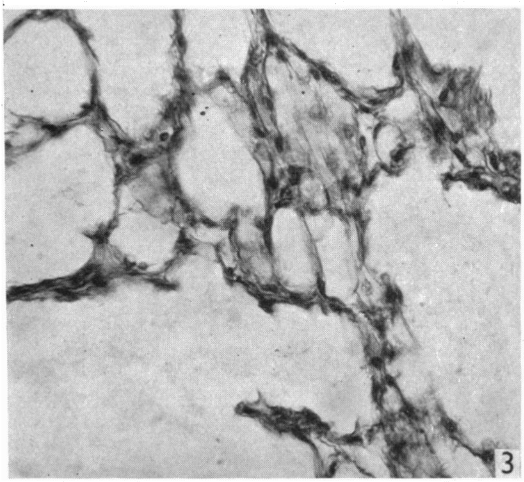
Fig. 7. Postnatal disc, 21 years. Lumbar region. Median sagittal section of nucleus pulposus showing loosely aggregated delicate fibrocartilage. Haematoxylin and eosin. ×80.

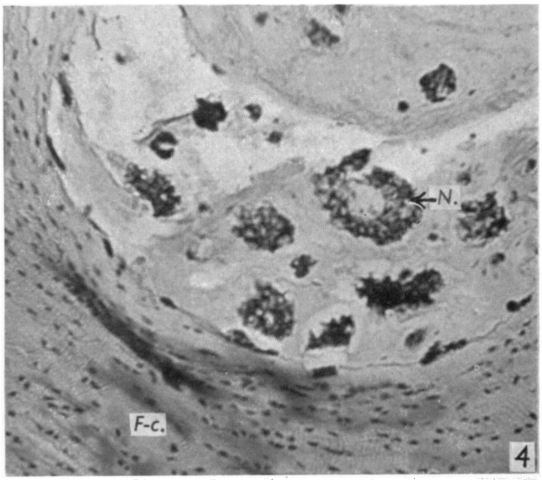
Fig. 8. Postnatal disc, 33 years. Lumbar region. Median sagittal section of nucleus pulposus showing fibrocartilage. Haematoxylin and eosin. ×80.

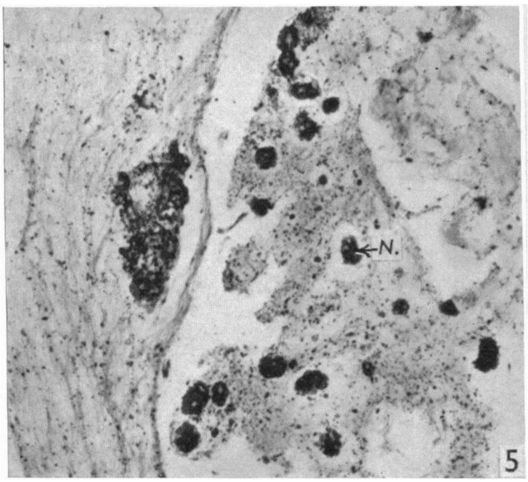
Fig. 9. Postnatal disc, 40 years. Lumbar region. Median sagittal section of nucleus pulposus showing fibrocartilage and nesting of cartilage cells. Masson's trichrome. ×100.

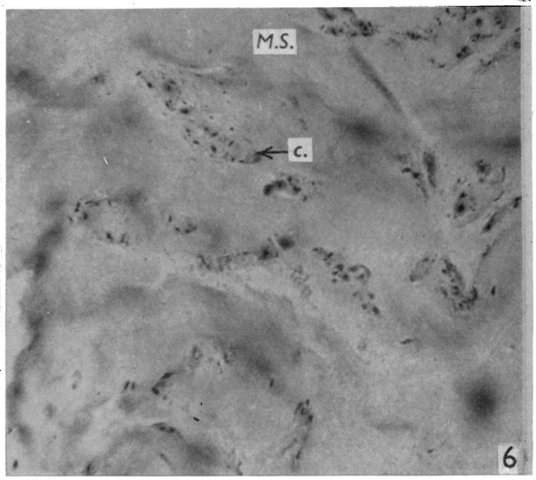
Fig. 10. Postnatal disc, 50 years. Lumbar region. Median sagittal section of nucleus pulposus showing cartilage cells with nests. Toluidin-blue. ×100.

Fig. 11. Postnatal disc, 64 years. Lumbar region. Median sagittal section of disc showing loss of clear demarcation between annulus and nucleus. Masson's trichrome. ×2·8.

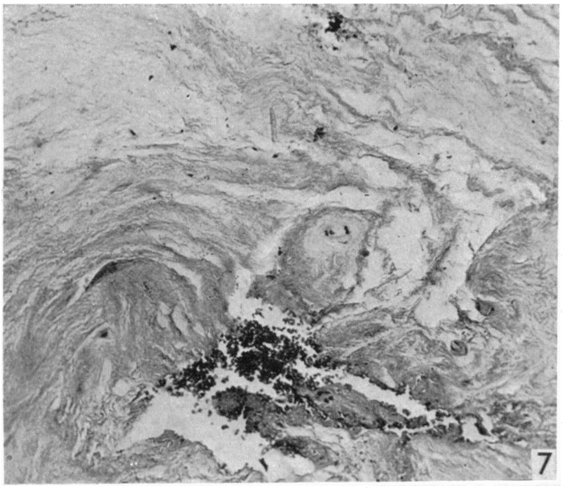


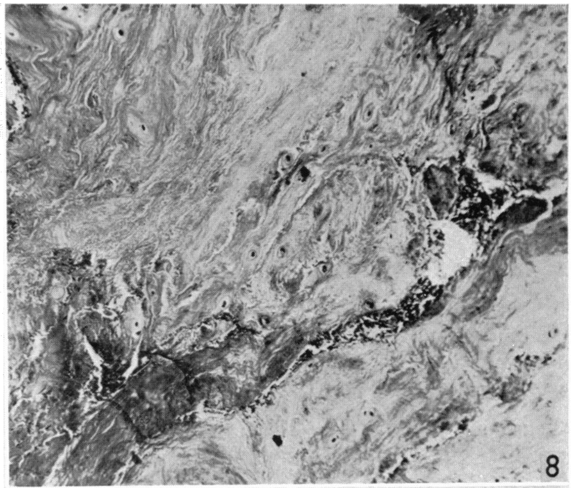


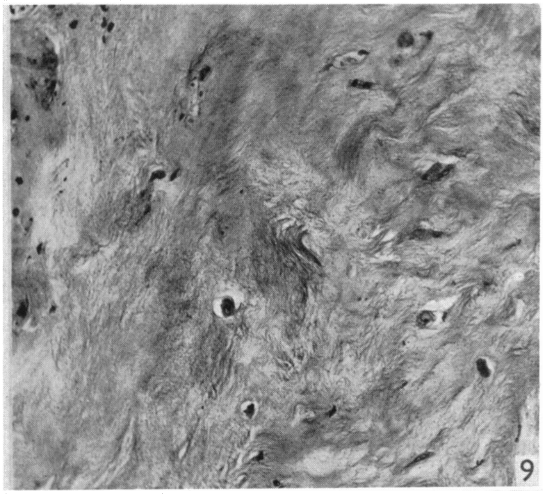


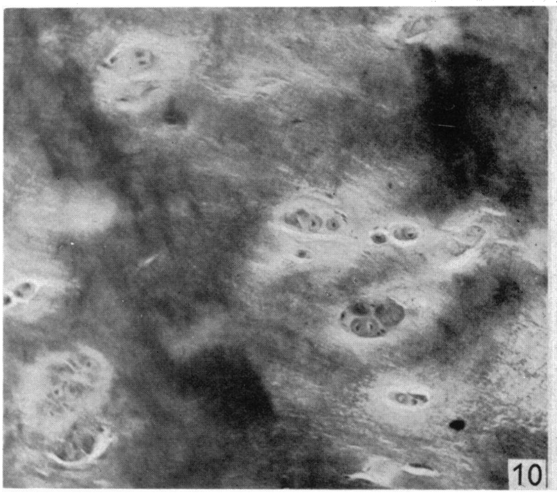


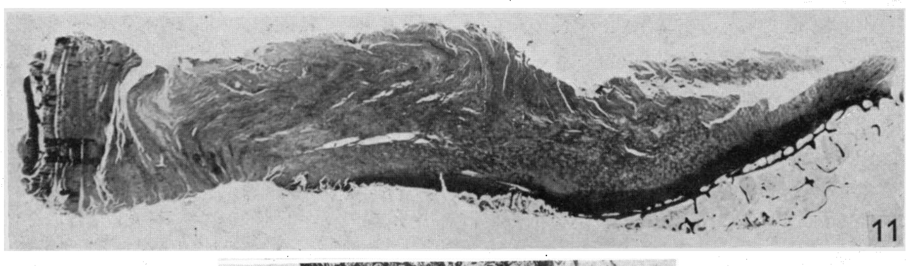
PEACOCK—OBSERVATIONS ON THE POSTNATAL STRUCTURE OF THE INTERVERTEBRAL DISC IN MAN



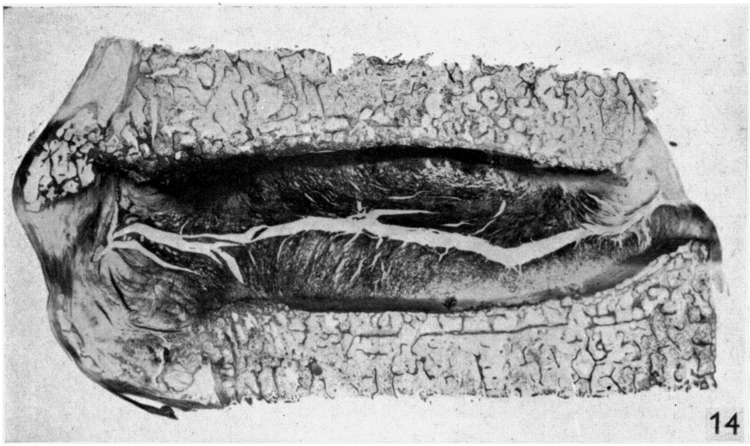


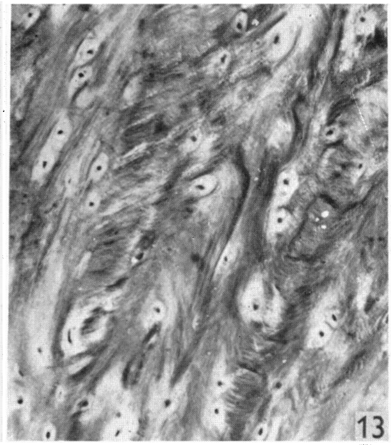


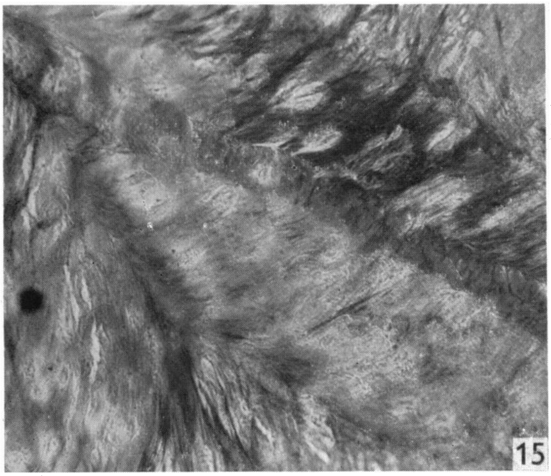


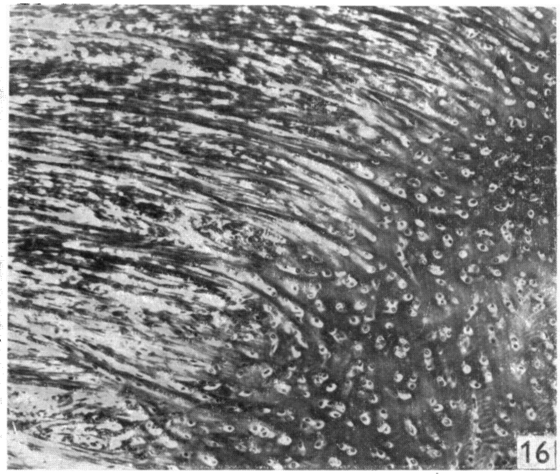


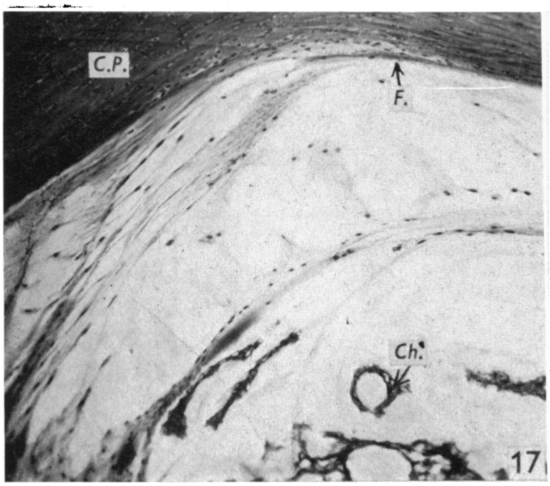
PEACOCK—Observations on the postnatal structure of the intervertebral disc in man

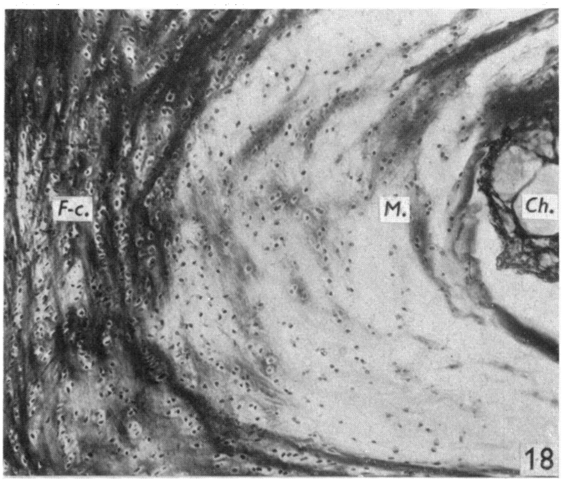












PEACOCK—OBSERVATIONS ON THE POSTNATAL STRUCTURE OF THE INTERVERTEBRAL DISC IN MAN

Fig. 12. Postnatal disc, 75 years. Lumbar region. Median sagittal section showing vertebrae and intervening disc and loss of demarcation between annulus and nucleus. Haematoxylin and eosin. $\frac{3}{4}$ natural size.

PLATE 3

Fig. 13. Postnatal disc, 75 years. Lumbar region. Median sagittal section of nucleus pulposus showing coarse fibrocartilage. Haematoxylin and eosin. ×180.

Fig. 14. Postnatal disc, 80 years. Lumbar region. Medial sagittal section showing loss of demarcation of annulus and nucleus and fissuring. Masson's trichrome. ×1·5.

Fig. 15. Postnatal disc, 80 years. Lumbar region. Medial sagittal section of nucleus pulposus showing indiscriminate arrangement and hyalinization of fibres, 'ghosts' of cartilage cells. Masson's trichrome. ×100.

Fig. 16. Full-term foetus. Lumbar disc. Median sagittal section of annulus fibrosus showing attachment of fibres of disc to cartilage plate. Masson's trichrome. ×73.

Fig. 17. Full-term foetus. Lumbar disc. Median sagittal section showing area of cartilage plate (*C.P.*) bounding nucleus superiorly, horizontal course of fibres (*F.*) in surface of plate turning down to join vertical component of annulus (transitional area). Chorda reticulum seen (*Ch.*). Masson's trichrome. ×73.

Fig. 18. Full-term foetus. Lumbar disc. Median sagittal section of disc showing transitional area between nucleus and annulus, notochordal reticulum (*Ch.*), separation of components of surrounding fibrocartilage (*F-c.*), mingling of the tissue components (*M.*). Masson's trichrome. ×73.