THE HYDRATION OF THE NUCLEUS PULPOSUS
AND ITS RELATION TO INTERVERTEBRAL DISC DERANGEMENT

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The natural history of the normal disc is well established. From the time of the earliest investigations (Uebermuth 1929, Puschel 1930, Junghanns 1931, von Puky 1937) it has been clear that the efficient functioning of the disc depends largely on the elasticity of the nucleus pulposus, and that this in turn is closely related to its water-binding capacity. In early life a water content of 80–88 per cent is usually quoted. From the fourth decade onwards an increasing proportion of subjects show a progressive lowering of the degree of hydration until, in late life, figures of 70 per cent may occur (Keyes and Compere 1932, Lindahl 1948). This change is usually accompanied by an alteration in the appearance of the nucleus, which becomes amorphous and sometimes discoloured, and then progressively more and more fibrotic until all trace of the normal highly elastic and highly hydrated gel is lost. Sylvén (1951) showed that the nucleus consists of a three-dimensional lattice of collagen fibrils in which is enmeshed a muco-protein gel. This protein-polysaccharide complex is responsible for the hydrophilia of the nucleus, and suffers a patchy loss, and disappearance of gel structure, as age advances. Large collagen bundles are laid down, with consequent lowering of the water content, until eventually, in advanced degeneration, the collagen may be completely devoid of mucoid material. The increased deposition of collagen, and possibly of elastin also, has been confirmed by other writers (Naylor, Happey and McRae 1954). This is therefore undoubtedly the abnormality that underlies and explains the dehydration occurring in the nucleus in later life. Although in general it occurs from the fourth decade onwards, it is not universal, and the persistence of a high water content into the sixth decade has been reported (Coventry, Ghormley and Kernohan 1945).

There is therefore a generally accepted concept of the process of "ageing" of the normal intervertebral disc, and considerable and growing understanding of the biochemical changes responsible for its gradually decreasing efficiency. In contrast, alterations in the behaviour and properties of protruded or extruded discs have received little attention. Deuchar and Love (1939) reported the microscopical appearances of 100 deranged discs removed at operation. They found degeneration of at least slight or moderate degree in almost every case, irrespective of age, and advanced changes in some cases in all age groups. These changes were "not infrequent" in specimens from young persons, and their occurrence rate increased only slightly with advancing age. Eckert and Decker (1947) published similar results. In forty "normal" discs from cadavers of all ages degenerative changes were not found in the first three decades, but had a gradually increasing incidence thereafter. In 182 mechanically deranged discs, on the other hand, changes were found irrespective of age, including surprisingly large areas of degeneration in material from several patients in the second decade. Such evidence as is available, therefore, suggests that, whether before or after displacement, deranged discs suffer either an acceleration of the normal ageing process or the action of some other factor which the normal disc escapes.

This paper pursues the same question by comparing the water-binding capacity (and therefore the functional efficiency) of normal discs obtained at necropsy with that of mechanically deranged discs obtained at laminectomy.
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PHYSICO-CHEMICAL BASIS OF WATER RETENTION WITHIN THE NUCLEUS

An essential preliminary to any investigation of this sort is an understanding of the mechanism whereby water is retained in the disc. There are two possibilities: osmotic pressure exerted by the individual molecules; and imbibition pressure exerted by the protein/polysaccharide gel. In general, the relation of these forces one to another is a complicated one, and I know of little published evidence concerning their relative importance in the disc. There has, however, been an almost universal tendency to assume that osmosis is the only factor, or, at least, the only important one. Inman and Saunders (1947) stated that the disc is to be regarded as an osmotic system in which the delicate mechanism of water balance can be upset by even minute tears in the annulus or the plates, with consequent interference with their function as semi-permeable membranes. The desiccation of the nucleus with advancing age is ascribed to decreasing permeability of the cartilage end-plates. Birkett (1950) summarised the published opinion up to that date and concurred, although less dogmatically, with the same view. Naylor and Smare (1953) suggested that the breakdown of complex molecules within the nucleus to produce simpler but more numerous ones would increase osmotic attraction, increase the pressure within the disc, and consequently cause or predispose to rupture of the annulus. A similar "hyper-hydration" mechanism had already been postulated by Charnley (1952), but with the reservation that he did not think that osmosis could be responsible for it. Bush, Horton, Smare and Naylor (1956) suggested that the water content was regulated by the balance obtaining between osmotic pressure differences on the one hand and the cohesive forces of the tissue on the other.

There are many difficulties in the way of accepting osmosis as the source of the hydrophilia of the nucleus pulposus. There is no doubt that molecular breakdown in an osmotic system would, as postulated by Naylor and Smare, result in increased osmotic pressure and increased hydration. In degeneration of the nucleus, however, the reverse effect has universally been observed, and degeneration and dehydration have consistently been found to proceed hand in hand. In longstanding osteoporosis of the spine and in some spinal fractures the vertebral end-plates may be ruptured and no longer semi-permeable, yet ballooning of the neighbouring space occurs and may be progressive. The narrowing of disc spaces after accidental damage to the annulus at lumbar puncture has been attributed to the loss of semi-permeability (Pease 1935, Haas 1939) but, as Milward and Grout (1936) pointed out in recording the same phenomenon, the time taken for changes to appear is too great to be explicable on the basis of water loss. In an osmotic system, dehydration could occur only as a result of changes in the semi-permeable membrane, yet gross alterations are commonly found in the nucleus of discs examined post-mortem, whereas cartilage plate defects are rare (Saunders and Inman 1940). Coventry, Ghorley and Kernohan (loc. cit.), in describing discs studied at necropsy, specifically referred to some in which the bulk and the water content of the nucleus were decreased without any abnormality being present in the annulus or end-plate. Finally, it seems most unlikely on teleological grounds that so heavily stressed a structure, whose function depended upon the maintenance of an intact osmotic system, would consist predominantly of extra-cellular material, for the whole nucleus would then be rendered ineffective by the smallest defect in the containing membrane.

When Charnley (loc. cit.) expressed doubt about the part played by osmosis, he supported his statement with the observation that disc substance immersed in four-times-normal saline increased in weight almost to the same extent as when immersed in normal saline. This finding in itself would serve almost completely to discount osmotic attraction as an effective force in disc hydration, but confirmation and some slight elaboration seemed desirable. Eight pieces of nucleus from young normal post-mortem spines were immersed successively for twenty-four hours in twice-normal, normal and half-normal saline, and then in water, and weighed after each immersion. Pieces of annulus of approximately the same size and shape from the same discs were similarly treated. In every case the annulus showed the
successive increases in weight that were to be expected on the basis of an osmotically controlled hydration: in no case did the nucleus do so. There was little difference in the pattern of weight change between individual discs, and a typical result is shown in Figure 1. The maximum weight for annulus and nucleus is expressed as 100, and the other weights as a percentage. It will be seen that this nucleus was able to maintain an almost constant degree of hydration in the face of changes in tonicity which caused a major alteration in the hydration of its annulus. This difference in behaviour can be attributed only to the muco-protein gel of the nucleus, and makes it virtually certain that the hydration of the nucleus is predominantly due to the imbibition pressure of the gel.

The remainder of the work to be described is based on the assumption that measurement of the imbibition pressure of a nucleus provides an accurate index of its efficiency.

THE NATURE OF IMBIBITION PRESSURE AND ITS MEASUREMENT

Standard text-books of colloid chemistry give full descriptions of imbibition pressure and emphasise its complete independence from osmosis. The short summary that follows has been compiled from Gortner (1938) and McBain (1950).

Gels have two constituents, a solid or “disperse” phase (the protein/polysaccharide complex in the case of the nucleus pulposus) and a “dispersions medium” (in this case tissue fluid). The affinity between the two constituents causes them to exhibit the phenomenon known as hydration, solvation or imbibition, and is such that a pressure, known as the imbibition pressure, is required to force them apart. If the gel is less than fully hydrated it will absorb its specific dispersions medium against this same pressure. The magnitude of the pressure varies inversely with the degree of saturation, being high when the gel is poorly hydrated and falling to zero when solvation becomes complete. Although there is no possibility of major degrees of dehydration ever occurring in a gel in the human body during life, it is interesting to note the enormous forces that can be brought into play by the solvation mechanism. A gel with a saturation of 1 per cent will have an imbibition pressure of the order of 5,000 atmospheres, and in complete dehydration of the disperse phase the pressure is theoretically infinite. It is this force which is responsible for the swelling of slippery elm. for the extraction of water from saturated salt solutions by dried gelatine, for the continued hydration of the cactus in spite of the osmotic pressure exerted by dry salty soil, for the
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ability of mushrooms to lift paving stones and dried peas to split rocks, and for many other familiar natural phenomena.

It is clear that this characteristic of gels provides a powerful and infinitely adaptable force to meet the functional needs of the intervertebral disc. It is indeed doubtful if any other mechanism could provide the strength, resilience and flexibility that are required.

Imbibition can be measured either by the weight increase occurring, or by the pressure developed, on immersion of the gel in its specific dispersions medium. Because of the progressive change in imbibition pressure as hydration proceeds, however, the initial degree of solvation must be known before any significance whatever can be attached to the result. Thus the isolated observation that a nucleus pulposus increases in weight or builds up a pressure on contact with saline or water indicates only that it was originally less than fully hydrated; it provides no information on the actual imbibition capacity of the nucleus, and no basis for the comparison of one nucleus with another. Failure to appreciate this has resulted, as will be seen later, in at least one widespread misconception concerning the hydrophilic properties of prolapsed discs.

![Image](image_url)

**FIG. 2**

To illustrate the relation between the successive weights of a specimen of disc material and the "imbibition indices" which are suggested as the best means of comparing one disc with another. The original weight (a), the fully hydrated weight (b) and the dry weight (c) combine to provide at (d) a representation of the hydrophilic power of one unit of dry weight of disc material.

**COMPARISON OF THE IMBIBITION PRESSURES OF NORMAL AND DERANGED DISCS**

In this investigation weight differences and the direct estimation of the ratio of pressure to degree of saturation were both employed. In each case the degree of saturation was determined by calculation from the dry weight of each nucleus. In order to avoid inaccuracies from de-naturing of the muco-protein in the course of drying, desiccation was carried out after all other estimations were complete.

**ESTIMATION OF IMBIBITION BY WEIGHT INCREASE**

Eighteen normal discs obtained post-mortem and seventy-five specimens from laminectomy were compared. The normals were taken from subjects between the ages of sixteen and thirty-five and were removed by section en bloc through the fourth lumbar vertebral body, the first
piece of the sacrum and the appropriate pedicles. The nuclei of the two lowest discs were thus available for investigation with the least possible exposure to air. A piece of each was excised, comparable in mass to the average laminectomy specimen, and cross-hatched to produce a surface of similar extent. Any disc showing evidence of a protrusion, or of discoloration or other naked-eye abnormality of the nucleus, was discarded. Six of the eighteen post-mortem discs, although normal in appearance, behaved in such a way as to suggest that they might more properly fall into a transitional group (Fig. 3). As the exact dividing line between normal and abnormal is, however, uncertain, it seemed best to continue to accept the naked-eye criteria and these six discs were included in the normal series. Similar imbibition characteristics were found in three other discs obtained post-mortem, which were excluded from the series on the grounds of discoloration and an abnormally granular appearance. It seems likely, therefore, that the microscopic appearances of such discs should be investigated in the future and might profitably be correlated with their imbibition capacity. The operation specimens were obtained from seventy-two patients aged between seventeen and forty-four; they were consecutive except for the exclusion of two which appeared to be entirely cartilaginous and therefore not comparable with the necropsy material. The indications

![Graph](image)

**Fig. 3**
To show the distribution of the effective imbibition index in seventy-five deranged and in eighteen normal discs. The six specimens whose indices fall between 13 and 16 may possibly form a transitional group.

for laminectomy had been the usual ones of failure to respond to, or early relapse after, adequate conservative treatment, and all derangements were therefore in an acute or "active" phase. At operation the disc substance was removed by pituitary rongeur or curette; the several fragments were collected on a gauze mop and then transferred to an airtight container to await weighing.

Each specimen, whether from operation or necropsy, was weighed, first in its fresh state, then after immersion in normal saline for twenty-four hours, and then after desiccation over anhydrous calcium chloride under reduced pressure. A comparison of the desiccated with the fully hydrated weight showed the maximum degree of saturation of which the nucleus was capable when free from pressure; and a comparison of the desiccated with the original weight indicated the degree of saturation which the nucleus had been able to maintain under the pressure obtaining in the disc space, or in the neural canal. The most convenient method of expressing these ratios, and of using them to compare one nucleus with another, is to take the desiccated weight in each case as unity and the other weights in proportion. Reference to Figure 2 will make this clear. This shows a representative normal disc, in which the excised portion of nucleus originally weighed 2.95 grammes. The weights after immersion and after
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Desiccation were respectively 3.32 grammes and 0.16 gramme. When the dry weight is taken as unity the original weight becomes 18.44 units and the fully hydrated weight 20.75. Figure 2 (d) therefore provides a representation of the hydrophilia of this nucleus, it being such that one unit of its dry substance could retain, in the conditions obtaining in the disc space, enough fluid to bring its weight to 18.44 units, and enough additional fluid, under conditions of free absorption, to increase its weight further to 20.75 units. Although the terms do not have general currency in the standard descriptions of the properties of gels, I suggest that, for the purpose of providing an accurate and easily determined means of comparing discs, the figures just quoted might properly be designated the "effective imbibition index" and the "free imbibition index" respectively. In so far as any one easily determined figure can do so, the former provides the most satisfactory measurement of the capacity of a nucleus to maintain its hydration, and therefore its efficiency, under its ordinary working circumstances.

A third figure is important as indicating the reaction of the nucleus to pressure, or other factors in its environment, and that is the difference between the effective and the free indices. This might be called the "imbibition differential," and it will be noted that a high value for this would indicate an undue susceptibility to outside influences—that is, a lowering of the efficiency of the water-binding mechanism.

It will be seen that the apparent water content of the nucleus, as determined above, is higher than that usually quoted. The discrepancy is probably to be accounted for by the escape of some free gel into the surrounding saline, which, during the period of immersion, always became opalescent. Some loss no doubt also occurred during the removal of surface moisture after immersion. These losses are unfortunately unavoidable if desiccation is postponed until other observations are complete, as is essential. They appear likely to affect all discs equally, and not to prejudice the comparison of one with another.

The imbibition characteristics of the normal (necropsy) and the deranged (operation) specimens were found to be markedly and uniformly different. As has already been shown, the effective imbibition index provides a measure of the water-binding capacity of the disc under what are probably its least arduous working conditions. In the normal group these indices lay between 13.3 and 22.4, with a mean of 17.1; whereas for the operation group the comparable figures were 3.4 to 12.7, with a mean of 7.9. The distribution throughout the two groups is shown in Figure 3, which makes clear the wide divergence between them. A less marked difference was found in the free indices, with mean figures of 21.2 (normal discs) and 14.7 (operation specimens). The "imbibition differential" was lower in the necropsy series (mean 4.1) and higher (mean 6.8) in the operative specimens. In this latter group individual differences were considerable and will be discussed in a later section. In spite of this variation, however, it is possible to give a reasonably accurate diagrammatic representation of the hydrophilic powers of an "average" prolapsed disc (Fig. 4). It will be seen that, even under conditions of free absorption, the deranged nucleus could fix much less fluid than the normal; and that under the conditions obtaining within the body, its water-binding capacity was even more markedly reduced. Its susceptibility to outside influences was greater in that a marked weight increase occurred on changing from bodily conditions to those of unhindered absorption. The significance of these findings is discussed below.
ESTIMATION OF IMBIBITION BY CORRELATING PRESSURE WITH THE DEGREE OF SATURATION

There are considerable technical difficulties in the way of obtaining a direct measurement of imbibition pressure in a heterogeneous structure such as a nucleus pulposus. Experiments with a hollow-bore needle communicating with the nucleus, either within the intervertebral space or in a rigid container, produced inconsistent results, and were not pursued. Fairly reliable figures could be produced at low loadings by simply placing the disc material in a syringe, weighting the piston and reading the volume changes on the syringe graduations. At even moderate pressures, however, jamming always occurred from the disc's insinuating itself between the piston and the barrel. An elaboration of this method proved fairly satisfactory—though occasionally somewhat temperamental—and reliable figures were eventually obtained for six normal and six protruded or extruded discs.

The weighed disc material was placed in a test tube with a perforated base; fine wire mesh, covered by a layer of filter paper, prevented extrusion through the perforations. The remainder of the tube was occupied by a balloon, filled with a watery solution of gentian violet and retained in place by a rigid clamp. The balloon was connected, through a graduated glass tube, to a mercury manometer, and the meniscus between mercury and gentian violet was adjusted to correspond with the lowest graduation in the tube when the pressure in the balloon was zero. With the test tube and its contained disc immersed in normal saline, increasing pressure was applied step by step to the disc, and the successive resulting changes in its volume were noted by the movement of the mercury/gentian violet meniscus. The pressure that could usefully be employed was limited by the difficulty of preventing extrusion of the balloon at the upper end of the test tube—that is, of ensuring that all recorded changes of volume took place only in the disc. Usually 50 centimetres of mercury was the approximate limit, but considerably higher pressures were reached once or twice. When the limit of pressure had been reached and the final volume reading obtained the disc material was removed and weighed. A comparison of its actual weight with that calculated from the volume changes provided a rigid check on any experimental errors. The disc was then desiccated as before and weighed again.

![Graph](image)

**Fig. 5**
Imbibition pressure saturation curves of representative normal and deranged discs.
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The figures so obtained formed a progression in which the pressure contributed by the disc could be related to its saturation at each successive step. Figure 5 is a graph showing the pressure/saturation curves of one cadaveric and one operation disc. The saturations are expressed by the ratio of weight : dry weight, and are therefore exactly comparable with the imbibition indices described above. The saturation shown at 0 centimetre Hg. is, of course, the "free imbition index."

The results yielded by this method, which in general conformed to the pattern shown in Figure 4, confirm those obtained by the simpler and probably more reliable weight-increase method, and add something to them. The discs obtained at operation were again markedly less hydrophilic than the normal, and they showed, particularly at low loadings, a greater than normal susceptibility to changes in pressure. It would be wrong to elaborate much on the results of so few cases, but it is of interest that, at a saturation corresponding to an imbition index of 10, the pressures contributed are 43 centimetres Hg. for the normal disc and only 11 centimetres Hg. for the operation specimen. Both these specimens came from subjects aged thirty.

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**Fig. 6**

To illustrate the range of imbition characteristics found in the series from the most hydrophilic (necropsy) specimen (a) to the least hydrophilic (operation) specimen (d).

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**RANGE OF VARIATION IN IMBITION CHARACTERISTICS, AND CORRELATION WITH THE CLINICAL HISTORY**

The imbition indices of discs removed at operation showed a fairly wide variation within the limits which have been described. In general, the various patterns of behaviour were such as to support the conception of a gradually progressive change, corresponding to the duration of the derangement. Without there being any sharp dividing line between them, three phases could be distinguished, and the correlation between these and the length of the clinical history was often surprisingly exact. This was particularly so in patients with a long history of continuous disability, and also, although to a lesser extent, in those with symptoms of recent onset. The intermediate phase often corresponded with a recurrent disability, but the intermittent nature of the history in that event made exact correlation difficult.

What is thought to be the earliest phase of this progressive abnormality is shown in Figure 6 (b). This represents the most hydrophilic specimen of the discs obtained at operation and came from a man of thirty-eight with a history of only two months of acute sciatic pain. Operation was necessitated by paresis of the antero-lateral group of muscles in the affected...
leg, advancing in spite of strict bed rest. Two completely separated portions of disc material were found, underlying an attenuated tensely bulging annulus, and weighing, together with a small quantity of curettings from the disc space, 4·83 grammes. The imbibition indices were 12·70 and 20·11. There were fifteen other specimens from patients whose histories extended over four months or less, and of these, eleven corresponded closely in type with the one illustrated—that is to say, they had a relatively high effective imbibition index and a high imbibition differential. A nucleus of this sort was capable, therefore, of retaining a normal or near normal amount of fluid when unstressed, but could not do so under the conditions obtaining in the intervertebral space; it seems reasonable to deduce from this that the gel was only moderately reduced in amount but was considerably reduced in efficiency. A similar imbibition pattern was found in two post-mortem discs, from subjects aged thirty-one to forty-four, which have already been mentioned and which were not included in the normal series because of brown discoloration of the nucleus.

At the opposite end of the scale of abnormalities were eight specimens of the type shown in Figure 6 (d), characterised by an effective index which was again rather higher than the average for deranged discs, but associated with a low imbibition differential. There was an absolute correlation between this imbibition pattern and a long clinical history, this group comprising all the six patients who had had a continuous disability for three years or more. Three patients were undergoing their second exploration at the same level, two of them after six years and one after ten. The specimen illustrated came from a man of fifty-two, who had a ten years' history of unremitting backache and sciatica. He had a large protrusion of the fourth lumbar disc, adherent to the fifth lumbar root, and yielding 5·62 grammes of material. These discs, in virtue of the very marked lowering of their capacity for free absorption, had an insusceptibility to pressure effects almost similar to that enjoyed by the normal disc at a high level of hydration. I suggest that this is probably to be explained by the gradual replacement of the gel with collagen, and that the next stage in the progression is one of fibrosis, hydrostatic inertness and clinical healing. This is to some extent borne out by the three specimens from second explorations, in which fibrosis could be expected to be most advanced. In these, the effective indices were 7·6, 7·8 and 7·9, with imbibition differentials of only 2·4, 2·3 and 2·6 respectively.

The remaining fifty-one discs obtained at operation occupied a position between the two extremes just described. It was in this group that the lowest effective indices were found, and the free indices were intermediate, ranging between 10 and 17. In general, these were the patients with the kind of history that most commonly precedes a laminectomy, with one or more attacks severe enough to require immobilisation during the few years preceding operation. The specimen illustrated in Figure 6 (c) was obtained from a patient aged thirty-eight, with a six months' history of sciatic pain immediately before operation, and a similar attack treated by a plaster jacket two years before. Figure 6, which in sum illustrates the extent of the variation in the imbibition characteristics of all the discs examined, is completed at (a) by the most hydrophilic of the normal series, obtained post-mortem from a subject aged sixteen.

**DISCUSSION**

A uniform finding throughout this series has been the lowered affinity for fluid shown by material from protruded or extruded discs irrespective of the patient's age. There seems little doubt that these changes must have preceded the mechanical derangement by a considerable period because no operation specimen, however short the clinical history, approached a normal degree of hydration at the time of its removal. It has already been stated that all operations were carried out when the patient was clinically in an acute phase, and there can be no question of the hydrophilia of the discs being substantially different at the time of actual protrusion. A further point is that no difference could be found between merely bulging discs and those
with a sequestrum lying free in the canal; in these latter cases, moreover, the sequestrum and the subsequent curettings from the disc space were in many instances examined separately and always gave closely comparable figures.

Two points, therefore, fall to be discussed, and will be taken in succession. First, the apparent conflict between the present findings and the commonly accepted view that disc protrusion is caused or contributed to by "hyper-hydration" or "engorgement" of the disc; and second, the effect which the described changes must have on the behaviour of the disc as a whole, before its derangement occurs.

The imbibition characteristics of discs, whether normal or abnormal, have usually been described in terms of the percentage increase in their weights occurring after their immersion in fluid. This increase is usually quite striking, as it was also in the present series of operation specimens. The discs shown in Figure 6 at (b) and (c), or the "average" example shown in Figure 4 (a), show increases ranging from about 40 per cent to over 100 per cent, and these figures are in accord with most published work. Comparison, on this basis only, with the relatively modest percentage increase of the normal disc (Fig. 4 (b)) could well lead to the conclusion that the deranged disc had in some way become more hydrophilic, and might be supposed to have generated some pressure in the intervertebral space, causing its protrusion. It is only when the true state of hydration is known by reference to the dry weight of material present that the fallacy of the above argument becomes apparent. When this is done it is clear that the high percentage increase of the abnormal disc indicates, not supersaturation, but an undue susceptibility to changes in environment; the large amount of fluid that it absorbs on removal from the body results from its inability to retain a normal amount when in the body. Far from "generating" an unusually high pressure, it reacts to increased pressure by losing an abnormally large volume of fluid.

The effects which this alteration in imbibition will have on the behaviour of the disc as a whole can be deduced with accuracy. Stresses transmitted through the vertebral bodies can be regarded as being resolved into two components: 1) a force balanced by the imbibition pressure of the nucleus, which will be wholly contributed by the nucleus; and 2) a residue which must be transmitted through or provided by the annulus. Hirsch (1951) pointed out that, if the nucleus "loses part of its faculty for producing an even distribution of pressure, the annulus is no longer capable of meeting even physiological demands made on it." It may be important also that in the normal disc at rest the "intrinsic pressure" of the nucleus (Petter 1933) is greater than the forces to be transmitted, and the annulus of such a disc would therefore be in tension and would experience compression only during activity. A reduction in the imbibition pressure of the nucleus will have three effects: 1) a greater proportion of the total strain will be thrown on the annulus; 2) the character of the strain may change from alternating tension and compression to unrelieved compression; and 3) under conditions of prolonged relaxation the disc will imbibie fluid, only to be unable to retain it when stress is reapplied. The first two factors are likely to cause gradual attrition of the annulus. The third factor will, on the application of strain, cause a sudden release of a volume of tissue fluid and a rapid redistribution of hydrostatic pressure, which will not easily be dissipated through the attenuated vascular communications of the disc.

I believe that these three factors provide in themselves a satisfactory explanation for most of the phenomena associated with disc protrusion. In particular, the sudden liberation of tissue fluid on loading a nucleus with a low imbibition pressure accords very well with the common history of the sudden onset of symptoms on first getting up in the morning, or with some trivial strain after a period of rest. There seems every reason to believe that repeated episodes of this kind would be sufficient to rupture an annulus which had already suffered damage from the action of the first two factors described above. Protrusion of the nucleus would follow, either gradually from weight bearing and movement or suddenly from another "hydrodynamic" episode. A minor corollary is that the reverse hydrostatic effect must
obtain when a pathological disc is freed from pressure, and may be the source of the "vacuum" disc phenomenon reported by Samuel (1948) and others.

CONCLUSIONS

The successive changes in imbibition pressure, which have been described above and illustrated in Figure 6, are exactly those which occur in an inorganic gel when it exhibits the phenomenon of "ageing." After maintaining their normal imbibition pressures for some time such gels pass first into a stage in which they can retain a near normal amount of fluid when unstressed, but cannot do so against pressure. A gradual decrease in the affinity between the phases then follows until finally the solid or disperse phase is able to bind to itself only a much reduced amount of its dispersions medium. The deranged discs in this series, therefore, exhibited changes which are to be ascribed to the loss of, or deterioration in, the muco-protein gel of the nucleus—that is, the same changes as have been shown by Sylvén (loc. cit.) and others to occur normally only with advancing years. If it be accepted, as I think it must, that these abnormalities preceded the mechanical derangement, then the etiology of disc displacement must include as a prime cause some unknown nutritional or biochemical factor which produces premature loss of, or deterioration in, the protein/polysaccharide complex of the nucleus. This is in agreement with the view put forward by Friberg (1948, 1950) after detailed anatomical and pathological work, that disc prolapse is to be regarded as evidence of earlier than normal degeneration.

The correlation of imbibition pressures with clinical history as summarised in Figure 6 makes it probable that the natural history of this premature ageing extends over a period of ten years or more. The progressive alteration in behaviour during that time can only be assumed, but it can be forecast with reasonable certainty from the data given in Figure 6, and expressed in terms of the effective imbibition index and of the expected variation in the fluid content of the nucleus under normal loadings (Fig. 7). It seems likely that the effective index represents very nearly the maximum degree of hydration which the nucleus can sustain within the intervertebral space; changes in water content under load would largely take place...
below this level but should be roughly proportional to the imbibition differential. Having regard to the shape of the imbibition curves shown in Figure 5, I have assumed that the normal variation under load amounts to half the imbibition differential, and on this basis have represented in Figure 7 my conception of the natural history of a disc as it passes, in the course of several years, from normal, through a prodromal phase, to an "active" phase and then into clinical healing. This may serve to summarise the theory of disc protrusion which is here presented. At the left of the figure the disc's characteristics are normal, with a high water content, a high degree of elasticity and a relatively small volume change under load. Abnormal muco-protein loss or deterioration then sets in (a) and the nucleus becomes both less well hydrated and more susceptible to the effects of pressure. This is the prodromal phase which, on the time basis suggested by Figure 6, appears to last perhaps for eighteen months. At (b) the annulus has already suffered a period of attrition, hydrostatic effects are at their greatest, with a markedly lowered index and maximal volume changes in the nucleus under pressure; the disc enters the phase of liability to protrusion, and continues so liable until at (c) the muco-protein loss and the collagen replacement are such that major hydrostatic effects cease. At (d) the disc is still markedly dehydrated but, in virtue of the replacement of gel by fibrous tissue, is now less susceptible to pressure than a normal disc; no actual functional reconstitution of the nucleus has occurred, but clinically there is healing. Whether or not a mechanical derangement actually occurs during the phase (b) to (c) will presumably depend on the age and activity of the patient at this point, on the extent and speed of collagen and fibrous tissue deposition in the nucleus, on the relation of annular damage and fibrosis to hydrostatic effects, and perhaps on unknown biochemical factors. It may well be that the difference between normal ageing and the process described here may reside simply in the two phases of muco-protein loss and collagen deposition becoming out of step. One can well imagine that a slow, orderly muco-protein loss, with collagen replacement proceeding pari passu, would allow progressive "physiological" dehydration to occur without damage to the annulus and without hydrostatic effects appearing.

I have concerned myself here purely with the mechanical effects that can be explained by, or deduced as following, premature muco-protein loss in the nucleus. I have little information as to whether or not additional biochemical factors enter into the production of the actual derangement. It is possible, but I think unlikely, that the nucleus, having become deficient in gel, becomes susceptible to electrolyte or other changes in the blood. I have immersed different portions of the same deranged disc in normal plasma and in the plasma from a patient suffering an extremely acute derangement, without any difference appearing between the two. Another possibility is that, as the imbibition pressure of the nucleus decreases, osmotic pressure becomes more important. This must certainly be true to some extent, but I should expect that, by the time degeneration had proceeded thus far, tears in the annulus or in the cartilaginous end-plates would have rendered the disc ineffective as an osmotic system. It seems, moreover, unnecessary on general principles to postulate two abnormalities when one provides an adequate explanation of the known facts.

**SUMMARY**

1. Eighteen normal discs from cadavers and seventy-five specimens of abnormal disc material obtained at laminectomy have been compared.
2. Imbibition pressure, and not osmotic pressure, is the important factor in maintaining hydration of the nucleus, and the comparison has been based on this finding. The terms "free imbibition index" and "effective imbibition index" are suggested as being readily determinable means of expressing the functional efficiency of a nucleus.
3. A reduction in imbibition pressure was a constant feature of the specimens obtained at operation. No evidence was found to support the theory that hyper-hydration or engorgement of the nucleus plays a part in disc protrusion. A reduction in imbibition pressure can, however,
be expected in itself, by a combination of mechanical and hydrostatic effects, to cause disc derangements.

4. The reduced imbibition pressure of abnormal discs is related to abnormal loss of, or deterioration in, the protein/poly saccharide of the nucleus. The premature onset of, or some disturbance in, the normal ageing process is a prime cause of mechanical derangement of the disc.

I owe special thanks to Mr. H. D. Griffith, B.A., F.R.S.E., Lecturer in Natural Philosophy, Aberdeen University, for bringing to my notice the facts concerning imbibition phenomena and for help in elaborating the theory of disc protrusion which is presented. My thanks are also due to Dr. A. Lyall, Head of the Department of Clinical Chemistry, Aberdeen University, for the use of apparatus; to Mr. A. M. Rennie for some of the operation specimens; to Professor J. Young for access to post-mortem material; and to Mr. Jack Watt for the provision of the post-mortem specimens. The preparation of the figures was greatly assisted by Mr. Topp of the Department of Clinical Photography.

Part of the work here described formed the basis of a short paper read before the British Orthopaedic Association in October 1954.

REFERENCES


THE JOURNAL OF BONE AND JOINT SURGERY