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Weight transmission through the sacrum in man

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INTRODUCTION

In recent years many studies (Adams & Hutton, 1980; Denis, 1983; Yang & King, 1984; Louis, 1985; Dietrich & Kurowski, 1985; Pal & Routal, 1986, 1987) have indicated the role of the neural arch in load transmission. Due to the high incidence of low back pain, spondylolisthesis and prolapse of intervertebral discs, the lumbosacral region has attracted the attention of many investigators. Probably Davis (1961) was the first to show that the pedicles and transverse processes at the level of L_5 are involved in transmission of compressive force to the pelvis. Adams & Hutton (1980), Yang & King (1984) and Pal & Routal (1987) found that at the lower lumbar region approximately about one fourth of the total load is borne by the neural arch. Dietrich & Kurowski (1985) are also of the opinion that although the vertebral bodies are the main load-bearing structures, the vertebral arches are also highly loaded elements. It is suspected that the cause of low back pain (Yang & King, 1984) and the mechanism of production of spondylolisthesis (Dietrich & Kurowski, 1985) are related to the transmission of considerable weight through the neural arch at the lower lumbar level.

Though the lower lumbar region has been extensively investigated, almost nothing is known about load transmission through the neural arch components of the sacrum (facet, pedicle, lamina and the transverse process element of the ala). Because of the change in morphology of the vertebrae in the sacral region and also because of the angled position of the sacrum in relation to the fifth lumbar vertebra it might be expected that the sacrum does not follow a similar pathway of load transfer as has been observed in the thoracic and lumbar region of the column (Pal & Routal, 1987).

In continuation of our previous studies (Pal & Routal, 1986, 1987) and using the same basic principles of estimation of weight transmission, load transmission in the sacrum was investigated. An attempt has also been made to find the route and the relative magnitude of weight passing through different components of the sacrum.

MATERIAL AND METHODS

Mathematical quantification of load

To study weight transmission in the sacrum the 44 adult columns studied in the previous investigations (Pal & Routal, 1986, 1987) were used.

In each sacrum, the surface area of the body, the two articular facets and the two auricular surfaces were measured by tracing their outline onto thin tracing paper. The area from the tracing paper was then measured with the help of a planimeter.

The mean surface areas (±S.D.) of the body, articular facets and the two auricular surfaces were calculated for 44 sacra. In addition to this, the areas of the two superior articular facets and that of the body were summed and compared with the total area of the two auricular surfaces in each sacrum. For the sake of convenience the summed area of the two superior articular facets and that of the body will be referred to as 'vertebral area' and the total area of the two auricular surfaces as 'iliac area'. Statistical analysis was applied to find the correlation between the vertebral area and the iliac area in each sacrum. In addition, three anomalous sacra were examined.

Trabecular pattern studies

The trabecular arrangement of the spongy bone corresponds closely to the direction of stress to which it is exposed (Koch, 1917; Lanyon, 1974). To investigate the involvement of the various parts of the sacrum in the route of load transmission, 10 sacra (2 young and incompletely ossified, 6 middle-aged and 2 old, with osteophytes) of the male sex were used. Trabecular bone was exposed by careful removal of the cortical bone with the help of a small bone nibbler. Exposed surfaces of the cancellous bone were examined and the direction of the trabeculae noted.

OBSERVATIONS

Measurements of articular areas

The mean surface area of the body was $12{\cdot}36 \pm 1{\cdot}65$ cm^2; the mean articular facet area $1{\cdot}97 \pm 0{\cdot}84$ cm^2 and the mean surface area of the two auricular surfaces was $18{\cdot}40 \pm 2{\cdot}19$ cm^2.

The mean of the areas of the body and the two superior articular facets (mean vertebral area of sacrum) was found to be $16{\cdot}30 \pm 2{\cdot}74$ cm^2. The mean iliac area of the sacrum, obtained by summing the areas of two auricular surfaces, was $18{\cdot}40 \pm 2{\cdot}19$ cm^2. The mean iliac area was thus $2{\cdot}10$ cm^2 more than the vertebral area. A significantly high correlation between the vertebral and iliac areas was observed ($r = 0{\cdot}88$; $t = 5{\cdot}77$; $P < 0{\cdot}001$).

Trabecular patterns

The following sets of trabeculae were observed in different parts of the sacrum.

(1) Strong trabeculae were observed extending from the superior surface of the body towards the auricular surface (Figs. 1, 2).

(2) Two distinct sets of trabeculae were seen to be extending from the articular process to the auricular surface. (a) One set of trabeculae on the dorsal aspect ran deep to the area for the attachment of the interosseous ligament (Fig. 3). (b) The other set, seen at the base, extended from the articular process and the pedicle towards the auricular surface at a deeper plane (Fig. 4, single arrow).

(3) A set of strong trabeculae, in the form of thin elongated plates arranged one upon the other, extended from the posterolateral angle of the ala (the site of attachment of the lumbosacral ligament) towards the body (Fig. 4, double arrow). This set of trabeculae was superficial to the set described above (2b). These two sets of the trabeculae, at the base of the sacrum, ran in different directions and were of different shapes. Trabeculae extending from the facet were in the form of rounded bars while the set extending from the posterolateral angle of the ala was in the form of thin elongated plates.

(4) Distinct trabeculae were also seen to be extending from the lateral portion of the laminae to the auricular surface.

These sets of trabeculae were found constantly in all sacra. No bilateral differences were observed and there were no age-related differences.

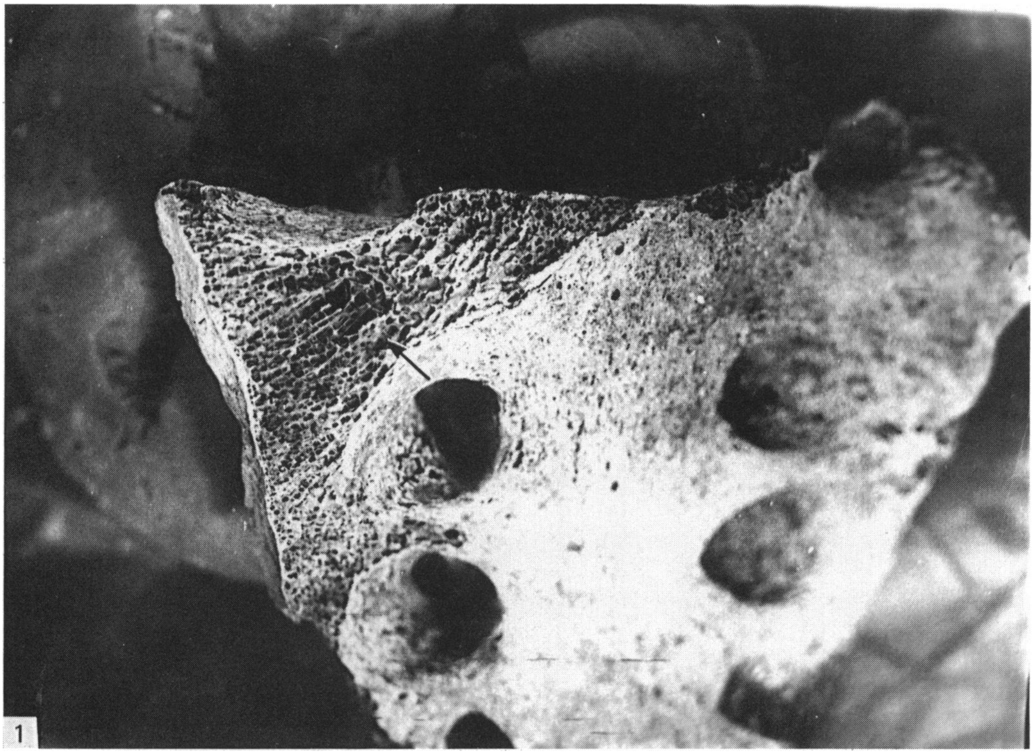

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Fig. 1. Trabeculae extend from the superior surface of the body to the auricular surface just beneath the cortical bone.

Observations on the anomalous sacra

Of the three anomalous sacra studied, two showed absence of an articular facet on one side and the third showed absence of the facets on both sides. In the absence of an articular facet the articular process was represented either as a small irregular bony mass or as a few bony spicules. An accessory articular facet was always present on the same side of the ala as that on which the articular facet was absent. This accessory facet was situated anteromedial to the site of attachment of the lumbosacral ligament (Fig. 5) on the ala and was approximately circular in shape with a rough elevated circumferential margin. It articulated with the transverse process of the fifth lumbar vertebra. In both cases of unilateral absence the surface area of the accessory articular facet(s) was approximately equal to the area of the normal articular facet on the other side (accessory facet 1·8 cm^2; 1·9 cm^2; normal facet 1·7 cm^2; 1·8 cm^2). The pedicle on the side of the anomalous articular process was very weak as compared to that on the normal side. A strong bony ridge was seen on the posterior aspect of the sacrum, extending from the posterior end of the accessory facet towards the lamina. In the specimen where both the articular facets were absent the areas of the accessory facets were 1·5 and 1·6 cm^2.

DISCUSSION

Quantification of load

The mechanical principles on which this quantification of load is based have been fully described in a previous paper (Pal & Routal, 1986).

The weight is transmitted to the sacrum at its body and its two articular facets and

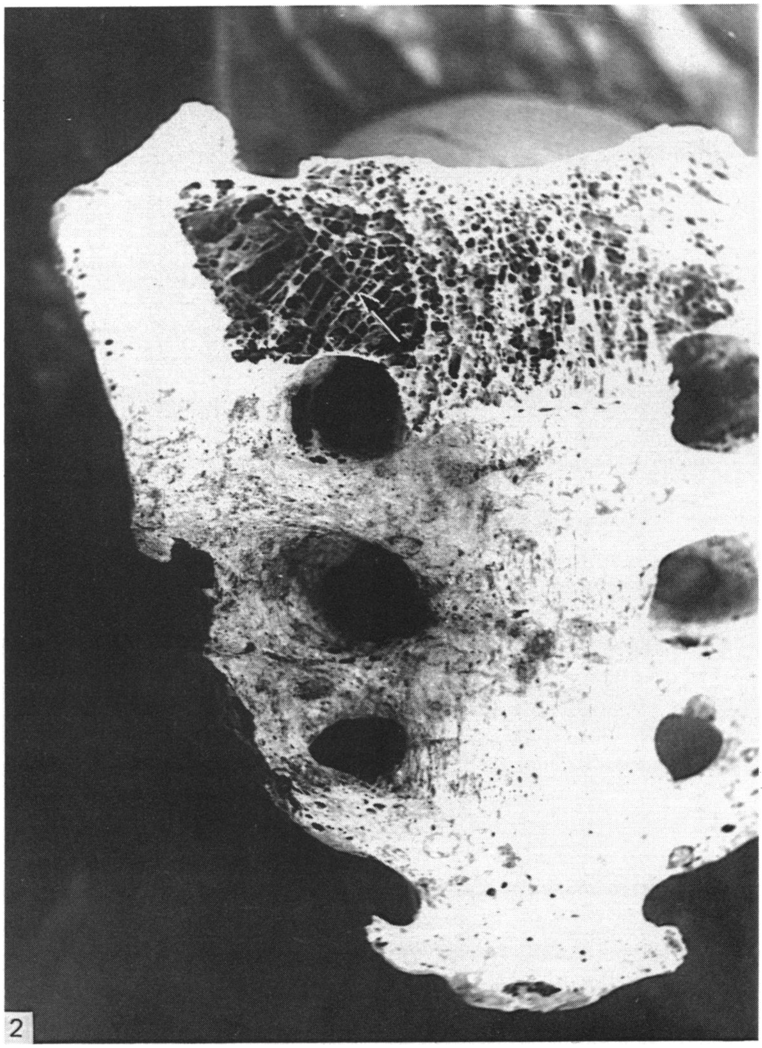

Fig. 2. Trabeculae extending at a deeper plane from the body to the auricular surface.

is transmitted to the hip bones through its two auricular surfaces. Assuming that the load transmitted through its two auricular surfaces is the same as that received at its body and its facets, there should be a correlation between the corresponding surface areas. Such a statistically significant correlation ($r = 0{\cdot}88$; $P < 0{\cdot}001$) between the vertebral area and the iliac area was, in fact, found and this suggests, indirectly, that the facets are involved in load transmission. If we consider that the iliac area (18·40 cm^2) represents 100% of the load passing out of the sacrum, then 67% of it is received through the body (12·36 cm^2) and 21% comes through the two articular facets (3·94 cm^2). The difference of 2·1 cm^2 between the vertebral area and the iliac area indicates that the magnitude of load passing out through the latter is 12% more than that received at the vertebral area. There are two possible reasons for this. Firstly, at each segmental level some new load is added to the column. However, the segmental increment at the sacrum should be minimal as the load from the sacrum is immediately transmitted to the two hip bones. Secondly, there is a possibility that a some of the

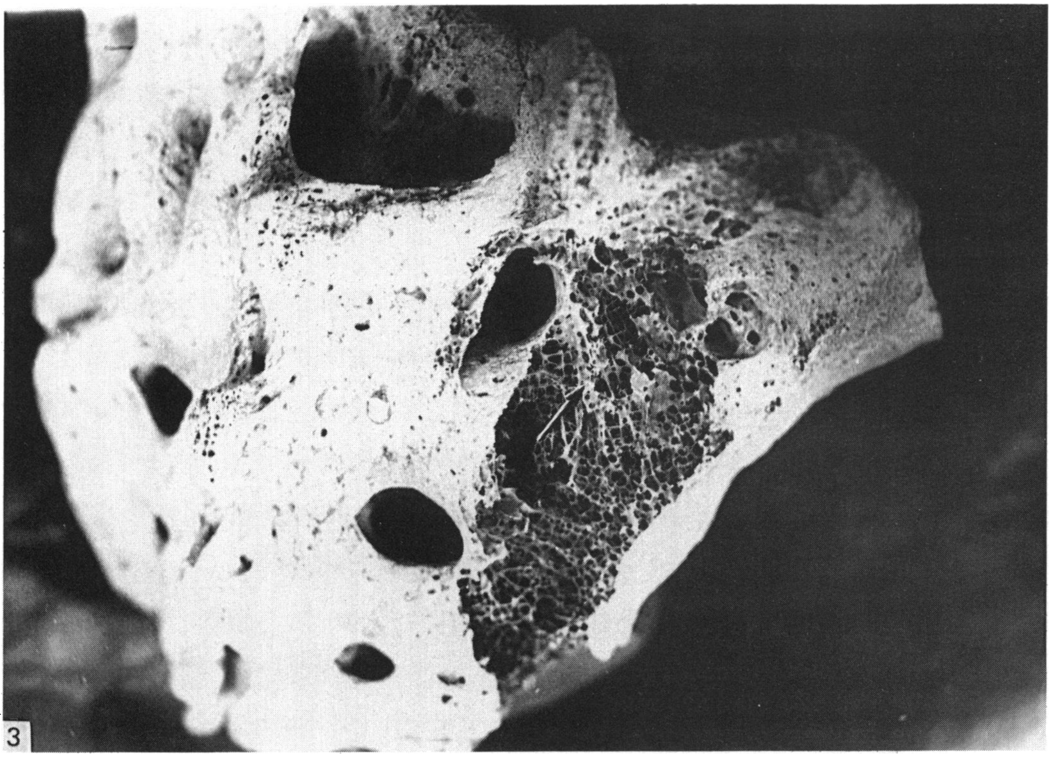

Fig. 3. A distinct set of trabeculae is seen running from the articular process to the auricular surface.

load is applied to the sacrum from some other source, possibly via the lumbosacral ligament.

Because of the angulation at the lumbosacral joint, the fifth lumbar vertebra has a tendency to slip forwards and this is resisted by the integrity of the lumbosacral joint, including the iliolumbar ligaments (Davis, 1961). Hence, a considerable load from the body of L_5 is transferred to the pelvis through the pedicles and transverse processes of the fifth lumbar vertebra (Davis, 1961; Pal & Routal, 1987). This concept is supported by the fact that the pedicles and transverse process of this vertebra are very strong and is also supported by the work of Pal, Leo & Routal (1988) who observed strong trabeculae extending from the body of the fifth lumbar vertebra to the transverse process via the pedicle. The iliolumbar ligament has two components, i.e. the iliolumbar ligament proper, which extends from the tip of the transverse process of the fifth lumbar vertebra to the iliac crest, and the lumbosacral ligament which extends from the inferior surface of the transverse process to the ala of the sacrum. The lumbosacral ligament is much stronger than the iliolumbar ligament proper and is quite capable of transmitting a considerable part of the load from the body of the fifth lumbar vertebra to the ala of the sacrum. This is supported by the finding of Pal, Leo & Routal (1988) that most of the trabeculae in the transverse process of the fifth lumbar vertebra are more prominent at its inferior border (site of attachment of lumbosacral ligament) than at its tip (site of attachment of iliolumbar ligament proper). The present investigation reveals the presence of a set of trabeculae extending from the site of attachment of the lumbosacral ligament (on the ala) to the body of the sacrum (Fig. 4, double arrow). These trabeculae must be involved in the transfer of

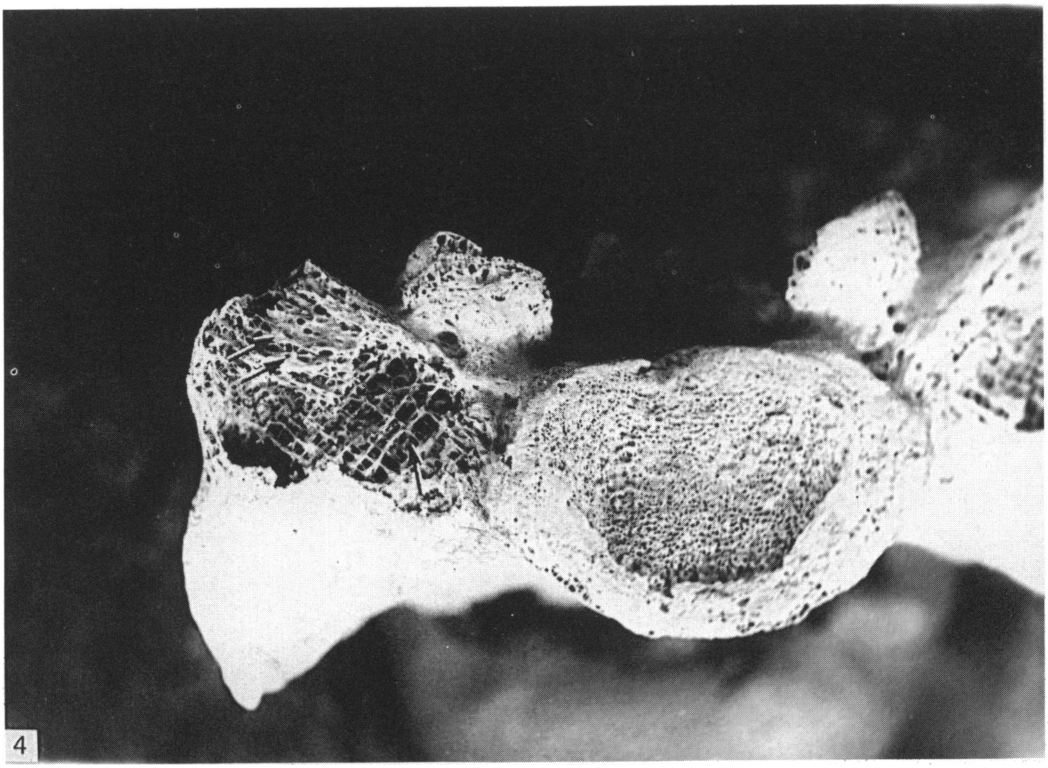
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Fig. 4. Two sets of the trabeculae are seen at the base of the sacrum. One set is extending from the articular process and pedicle towards the auricular surface (single arrow) while the other set is extending from the posterolateral angle of the ala (site of attachment of lumbosacral ligament) towards the body (double arrow). The superficial set (double arrow) was removed in its medial half to expose the deeper set (single arrow). Note the difference in direction and morphology of trabeculae of the two sets.

load from the lumbosacral ligament towards the body of the sacrum. The 2·10 cm^2 excess area of the iliac as opposed to the vertebral surface (equivalent to 12% of total load) is thus due to the load brought by the lumbosacral ligaments.

An estimate of the relative magnitude of load, transmitted through the iliolumbar ligament, may be made by referring to the work of Pal & Routal (1987). The articular facet area gradually increases from L_4 to S_1 (L_4, 1·69; L_5, 1·93; S_1, 1·97 cm^2), indicating that the load passing through the facets gradually increases from above downwards. However, the surface areas of the bodies show a sharp fall from L_4 to S_1 (L_4, 14·17; L_5, 14·07; S_1 12·35 cm^2), indicating that a considerable proportion of the load is transmitted other than through the bodies and it is suggested that this load is transmitted to the pelvis from the body of the fifth lumbar vertebra through the iliolumbar ligament. If we deduct the surface area of S_1 (12·35 cm^2) from the area of the inferior surface of L_4 (14·17 cm^2) a difference of 1·81 cm^2 is obtained. The load equivalent to 1·81 cm^2 area is thus presumably passing out through the iliolumbar ligament. The share of the load carried by each of the two components of the iliolumbar ligament will depend on their relative strength. Since the iliolumbar ligament proper is relatively weak (it is an anteroposteriorly flattened aponeurotic sheet) as compared to the lumbosacral ligament (a thick band of fibres) it is to be expected that a major part of the load will be transmitted through the latter

Fig. 5. Specimen showing the absence of the articular facet on one side and the presence of an accessory facet on the ala on the same side.

component. These calculations thus confirm the findings of Davis (1961) and Pal & Routal (1987).

Morphological evidences for the role of the neural arch in load transmission and its route

Trabecular pattern

The trabecular pattern in the sacrum has not been investigated before. From all the weight-bearing areas of the sacrum at its base (body, facets and alae), trabeculae extend towards the auricular surface. The morphological structure of the two sets of trabeculae, seen at the base of the sacrum (Fig. 4) is different and they also run in two different planes. This is because the facet (and also the trabeculae extending from the facet to the auricular surface) is subjected to compressive forces while the site of attachment of the lumbosacral ligament at the ala (and also trabeculae extending from it) is subjected to tensile pull due to the sliding tendency of the fifth lumbar vertebra.

Sacra with anomalous articular facets

Since 21 % of the total load is borne by the articular facets, in the absence of one or both of the facets this load is likely to reach the sacrum through the accessory articulation between the ala and transverse process of the fifth lumbar vertebra. Surprisingly the relative magnitude of the load passing through two sides of the neural arch elements (pedicle and transverse process element) was symmetrical in the anomalous sacra as indicated by the almost identical surface area of the normal articular facet and the accessory articular area on the ala. In the specimen where articular facets were absent on both sides a symmetry in load transmission through accessory articulations was again observed. These findings indicate that the magnitude of load borne by the transverse elements, on the anomalous side of the sacrum, is not shared by the body or by the other half of the neural arch elements (articular process, pedicle, transverse process element and lamina). However, this may be true only for L_5–S_1 level as the tendency to transmit the load from the body to its transverse processes is unique to the fifth lumbar vertebra.

The probable role of the pedicle, in the sacrum, is to transmit the load from articular facet to body and ala. This is indicated by the presence of a weak pedicle on the side of the absent articular facet, as it is not involved in transmission of load. The presence of a ridge on the posterior aspect of the sacrum (extending from the accessory articular facet on the ala to the lamina) indicates that a part of the load from the accessory facet is going towards the lamina; this would otherwise have gone through the normal facet joint.

SUMMARY

An attempt has been made to find the route and relative magnitude of weight passing through different components of the sacrum. In 44 adult male dry sacra, the combined surface area of the body and the two facets was compared with the combined surface area of the two auricular surfaces. It was found that the forces acting on the body and articular facets, at the upper end of the sacrum, are ultimately transmitted through the two auricular surfaces with an appreciable part of the load passing directly from the transverse process of the fifth lumbar vertebra to the ala of the sacrum through the lumbosacral ligament.

The direction of the trabecular bone indicates the route of load transmission in the sacrum. From the various parts of the sacrum (body, facets, alae and laminae) distinct sets of trabeculae extend towards the auricular surface. Observations on the sacra with the anomalous articular processes provided strong evidence for the role of the neural arch elements in the load transmission. In specimens where the articular facet was absent on one or both sides, there was always an accessory facet on the ala of the sacrum so that the load was transmitted to this facet from the transverse process of the fifth lumbar vertebra.

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