THE STRUCTURE OF THE VERTEBRAL SPONGIOSA

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The vertebral spongiosa, or the cancellous bone of the vertebral bodies, was described by Schmorl (Schmorl and Junghanns 1959) as “consisting of thin bone plates intersecting each other and perforated by numerous openings varying from roughly circular to quadrangular in shape.” Schmorl also noted that the number and direction of the plates varied in different parts of the spine and under different conditions of spinal curvature, and attributed these variations to differences in functional stresses.

There is little published information on quantitative aspects of the structure of the vertebral spongiosa. Eder (1960) made studies of the thickness of the bony plates, and of the distances separating them, in eighty-three post-mortem specimens: he found an increased separation and a slight decrease in plate thickness with increasing age. Caldwell (1962), in a radiographic study of slices of bone from vertebral bodies, and Arnold (1964), who determined the ash content of the vertebral spongiosa, demonstrated a decrease in the amount of bone present (that is, the proportion of the total tissue volume occupied by bony structures, as opposed to bone marrow) with increasing age. Dunnill, Anderson and Whitehead (1967), studying histological sections which included both the cortical and cancellous bone of the second lumbar vertebral body in post-mortem specimens from ninety-five apparently normal subjects, also demonstrated a decrease with age in the “percentage volume of bone,” the magnitude of the change being approximately the same as that reported by Sissons, Holley and Heighway (1967) for the cancellous bone of the iliac crest. Atkinson (1967), in a radiographic study of slices of bone from the second lumbar vertebral body in post-mortem specimens from sixty-eight subjects, found a progressive loss of bone after fifty years of age.

MATERIAL AND METHODS

Studies were made of the amount and arrangement of the cancellous bone in the body of the third lumbar vertebra of a normal twenty-year-old woman. The vertebra was obtained at necropsy following sudden death due to head injuries: it was fixed in formalin and sectioned with a band saw (Fig. 1). A vertical block of cancellous bone tissue from the central part of the left half of the vertebral body (P.1), extending from the superior to the inferior vertebral plate, and measuring approximately $6 \times 7$ millimetres in cross-section, was decalcified in ethylene diamine tetra-acetic acid at pH 7 and embedded in celloidin for serial histological sectioning and reconstruction. The right half of the vertebral body was divided into a series of transverse (horizontal) slices, each approximately 3 millimetres in thickness, as shown in Figure 2. Two of these slices (P.2 and P.5), and the central sagittal slice (H), were embedded in celloidin for histological sectioning. The remainder were macerated in dilute alkali for low-power microscopic study of the bony structures. All the histological sections were stained with haematoxylin and eosin.

The block P.1 was used to prepare a continuous series of transverse serial sections, extending from the superior to the inferior surface of the vertebral body. The sections were made rather thick, to simplify the task of reconstruction. There were 809 sections, and their average thickness, determined from the actual length of the block, was 27.2 μ. Using the serial sections, four enlarged models of the cancellous bone tissue were prepared by usual reconstruction techniques: each corresponded to thirty-two sections, and thus to a height
of approximately 0.9 millimetre. The enlarged image of each section was projected onto a thin (0.75 millimetre) sheet of white polyvinyl chloride plastic material, and the outline of the bony structures was traced by hand. The magnification chosen (×31.3) was the ratio of the thickness of the plastic sheet to that of the sections, in order to achieve the same vertical and horizontal scale for the final model. In fact, the models were slightly less in vertical height than predicted (average 8.4 per cent), due to variation in the thickness of the plastic sheet and to surface plasticisation when the sheets were finally glued together. A contact photographic copy of each outline drawing was prepared for later use in connection with the assembly of the model and certain of the histological measurements. The "marrow" areas in each plastic sheet were then cut away with a high-speed tungsten carbide drill, the process being controlled by inspection with a low-power binocular microscope. The remaining "trabecular" structures were then assembled on a transparent plastic base plate, using the photographic copies of the outline drawings to maintain correct alignment: this was done by temporarily attaching each set of structures to the corresponding outline drawing, holding the assembly in a jig to maintain the position relative to the rest of the model, and gluing each layer to the previous one with a plastic adhesive cement. In Models 1 and 2, each serial section was represented by a plastic sheet; with Models 3 and 4, alternate serial sections were used and the plastic sheets were twice the thickness of those used in the other models. Both types of model gave a reasonably close approximation to the outline of bony structures, and no attempt was made to smooth off the bony surfaces in the final models.
A measure of the amount of bone present in each of the sections (the proportion of the total tissue volume occupied by bony structures) was obtained by weighing the plastic sheets before and after removing the marrow areas: this is termed the 'bone area.' The surface area of the bony structures in each of the sections (mm.$^2$/mm.$^2$ of tissue, or mm.$^{-1}$) was determined from the outline drawings, using the line sampling technique described by Curtis (1960) and by Hennig (1958), counting 450–600 intercepts for each section. The width of the bony structures, and of the spaces between them, were similarly determined, measurements being made in both the antero-posterior and transverse directions: plate intersections and junctions were excluded. Measurements of bone area were made on all the sections (thirty-two in number) used for each model: measurements of surface area were made on five to fourteen representative sections from each set of thirty-two, and these sections were also used for the measurement of widths of bony structures and spaces.

Outline drawings were also prepared from sections of slices H, P.2 and P.5, and measurements were made from them.

**OBSERVATIONS**

The bony structures making up the vertebral spongiosa are arranged in a complex and rather variable pattern which eludes a simple and precise description. Figures 3 to 5 show that the spongiosa consists of intersecting curved plates which contain rounded perforations of varying size. The orientation of the plates depends on their exact position within the vertebral body, but vertical and horizontal structures predominate and are responsible for the appearance of vertical and horizontal "trabeculae" in a histological section in the sagittal plane (Fig. 9). It must be emphasised, however, that even in the more porous areas (Figs. 4 and 5) the basic structure consists of perforated plates rather than true trabeculae in the sense of struts or bars.

In the regions near the superior and inferior surfaces of the vertebral body, the bone structure is more dense than in the intervening central region (Figs. 3, 4, 6, 7, 8 and 9).
is due to increased thickness of the horizontal plates and to their relatively close arrangement, and is particularly prominent in the central area of the lower part of the vertebral body (Fig 9).

In the anterior and upper part of the vertebral body, the bony plates have a predominantly radial orientation (Fig. 6): posteriorly they consolidate to form the pedicle of the vertebra.

There is considerable variation in the thickness of the bony plates, and in the shape and size of the perforations in them (Figs. 3 to 5). The basic fenestration is roughly circular, oval or rectangular, the arrangement at times resembling a flattened tube. It should be noted
that the fenestration or perforation in the vertical plates is synonymous with the spacing between horizontal plates: conversely the fenestration or perforation in the horizontal plates corresponds with the spacing between vertical plates. The structures making up the spongiosa of the central part of the vertebral body (Fig. 5) have smooth outlines with junctional "filleting" where plates intersect. Occasionally, plates are seen which end abruptly at a distance from other structures. This absence of continuity may possibly be the result of recent bone remodelling, but this point was not specifically investigated.
Study of macerated slices from lumbar vertebrae from a number of other young adults showed a generally similar arrangement of the spongiosa.

ANALYSIS OF MODELS

Findings in the four reconstructed regions illustrate the range of appearances encountered in different parts of the vertebral bodies. Model 1 (Fig. 10), from the region just above the inferior surface, shows a dense bony structure made up of predominantly horizontal plates: these are thick, and fenestration is not pronounced. Model 4 (Fig. 13), from the region just below the superior surface, shows a somewhat similar appearance, but fenestration is more pronounced and results in the presence of more regular tube-like bony structures. Models 2 and 3 (Figs. 11 and 12), from the central part of the vertebral body, show a change to predominantly vertical plates: these are more widely spaced (greater horizontal pore size) and the general arrangement is characterised by greater economy of bone, particularly at the junctions of tubes or plates.

The results for the measurements of the amount of bone, for the surface area of the bony structures and for the thickness and spacing of the spongiosa, allow a comparison between the four regions studied. The figures for bone area (Table I) confirm the relative density of the bone near the superior and inferior surfaces of the vertebra (Models 4 and 1) when compared with the more central part (Models 2 and 3). Values for individual sections ranged from 16.5 per cent in Model 3 to 44.5 per cent in Model 1. The total surface area of the bony structures (Table I) ranged from 2.57 to 3.75 mm. $^{-1}$ in terms of the total volume of tissue, and from 13.6 to 15.6 mm. $^{-1}$ in terms of the actual volume of solid bone. The differences between the four models were not significant. The plate thickness, measured in the antero-posterior and transverse direction (Table II), ranged from 0.11 to 0.16 millimetre. The differences between the four models, though not great, were significant (P values between 0.01 and 0.1), the central, relatively porous, part of the vertebral body having the greatest mean value for plate thickness. The separation between the plates (pore size), measured in the same directions as plate thickness (Table II), ranged from 0.54 to 1.16 millimetres, and was greatest in the central part of the vertebral body (Model 3): the differences between the four models were all highly
significant (P > 0.001). Except for Model 4, there were significant differences between the pore size for the most dense and the most porous areas within each model.

![Fig. 10](image)

**Fig. 10**
Photograph of Model 1. Note the predominantly horizontal orientation of plates, particularly at the left of the picture.

![Fig. 11](image)

**Fig. 11**
Photograph of Model 2. Note the more vertical orientation of plates, and the wider spacing.

The relationship between bone area and surface area is of interest. The pairs of values for these two parameters for individual sections from the four regions studied are shown in Figure 14. In all, values for thirty-two sections were available. As the bone area increases,
the surface area increases to a maximum value of approximately 4 mm., corresponding to a bone area of 30 to 35 per cent; with higher values for bone area the surface area decreases.

![Figure 12](image1.png)

**Fig. 12**
Photograph of Model 3. Plates are still vertically oriented, and even more widely spaced.

![Figure 13](image2.png)

**Fig. 13**
Photograph of Model 4. In comparison with Figures 11 and 12 the bone structure is more dense, and horizontally oriented plates are seen. The spacing is reduced, and smaller tubular structures are apparent.

When the results for surface area are expressed in terms of the volume of solid bone instead of that of the whole tissue (Fig. 15), a different relationship is seen. As the bone area increases, the surface area per unit volume of bone decreases throughout the range of values observed:
that is, the denser the bone tissue the less the available surface area provided by a standard volume of calcified bone.

**DISCUSSION**

The precise mechanical consequences of the structural patterns described for the vertebral spongiosa are not clear, although it seems that the open network of intersecting plates combines resistance to compressive stress with economy of structural material and consequent lightness.

The preferential orientation of plates in the vertical and horizontal planes appears to be related to the assumed vertical orientation of stresses in the spine, and the work of Bell, Dunbar and Beck (1967) has shown the important role of transverse, as well as vertical,

<table>
<thead>
<tr>
<th>Model</th>
<th>Bone area (per cent) Mean and S.E.</th>
<th>Surface area per unit volume tissue (mm. sq.) Mean and S.E.</th>
<th>Surface area per unit volume bone (mm. sq.) Mean and S.E.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>33.0 (1.0)</td>
<td>3.75 (0.14)</td>
<td>15.6 (0.58)</td>
</tr>
<tr>
<td>2</td>
<td>23.1 (0.2)</td>
<td>3.33 (0.08)</td>
<td>14.7 (0.58)</td>
</tr>
<tr>
<td>3</td>
<td>19.1 (0.4)</td>
<td>2.57 (0.06)</td>
<td>13.6 (0.42)</td>
</tr>
<tr>
<td>4</td>
<td>24.4 (0.7)</td>
<td>3.70 (0.06)</td>
<td>15.0 (0.95)</td>
</tr>
</tbody>
</table>

**TABLE II**

<table>
<thead>
<tr>
<th>Model</th>
<th>Plate thickness (millimetres) Range and mean</th>
<th>Pore size (millimetres) Range and mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.12-0.16 (0.13)</td>
<td>0.54-0.83 (0.65)</td>
</tr>
<tr>
<td>2</td>
<td>0.12-0.14 (0.13)</td>
<td>0.73-0.95 (0.87)</td>
</tr>
<tr>
<td>3</td>
<td>0.13-0.15 (0.14)</td>
<td>0.94-1.16 (1.02)</td>
</tr>
<tr>
<td>4</td>
<td>0.11-0.12 (0.12)</td>
<td>0.68-0.74 (0.72)</td>
</tr>
</tbody>
</table>

structures in resisting such stresses. However, the type of structure described in the present study, with plates inclined in many directions and joining together at various angles, would serve to protect the vertebra against compressive stresses in other directions, and against shearing stresses in various planes. It may be that the predominantly vertical and horizontal orientation described may be related, at least in part, to the planes of sectioning adopted in the present study: these were all either vertical (Slab H, Figs. 8 and 9) or horizontal (Models 1 to 4, Slabs P.2-P.8), and it would be of interest to know whether oblique sections might isolate or emphasise parts of the spongiosa oriented in other planes.

The values for bone area are, on the whole, higher than those reported by Sissons, Holley and Heighway (1967) for the cancellous bone of the iliac crest (15 to 25 per cent for young adult individuals). The discrepancy appears to be explained by the increased density of bone towards the upper and lower surfaces of the vertebra, the values for the more central parts corresponding more closely to those reported for the iliac crest.

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It is of interest to note that the maximum surface area, in terms of the total tissue volume, is, for the vertebra studied, provided by regions of tissue where the bone area is approximately 30 to 35 per cent.

**FIG. 14**

Relationship between bone area (percentage of section area occupied by bone) and surface area (mm²/mm³ of tissue) for the thirty-two sections from different parts of the vertebral body.

**FIG. 15**

Relationship between bone area (percentage of section area occupied by bone) and surface area (mm²/mm³ of bone) for the thirty-two sections from different parts of the vertebral body.

**SUMMARY**

1. The structure of the cancellous bone of the third lumbar vertebral body from a twenty-year-old woman who died from head injuries was studied, using serial section reconstruction techniques.
2. In addition to the construction of enlarged models from different regions of the vertebral body, measurements were made of the bone area, the surface area, and the thickness and spacing of the bony structures.

3. The vertebral spongiosa consists of a complex network of bony plates perforated by rounded openings of varying size. The plates show preferential orientation in the vertical and horizontal planes, and the amount of bone is greatest towards the upper and lower surfaces of the vertebral body.

4. The mechanical significance of the structure of the vertebral spongiosa is discussed.

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REFERENCES


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