Numerical density and distributional pattern of dentin tubules

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Fosse G, Sæle PK, Eide R. Numerical density and distributional pattern of dentin tubules. Acta Odontol Scand 1992;50;201–210. Oslo. ISSN 0001-6357.

By a new method the numerical density and distributional pattern of transversely cut dentin tubules and the diameters of their peritubular dentin walls were measured in sections near the dentin–enamel junction (DEJ), midway to the pulp, and near the pulp wall in human premolars. For each section the mean and standard deviation of these variables were expressed. At all three levels the measurements comprised the same bundle of tubules from the DEJ to pulp in the coronal dentin. The number of tubules per square millimeter increased more than three times, and the diameters of peritubular dentin decreased one-tenth, whereas central distances between tubules were halved from DEJ to pulp. Thus the pulpward reduction of intertubular dentin is quantified. The distribution of the tubules is not regularly hexagonal, but the distances between them at each given depth are still very uniform in all directions. The pattern of cross-cut tubules often showed distinct short curved rows. The quantitative method might be used to determine taxonomic affinities. □ *Dentin; morphometry; peritubular dentin; tubules*

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Ketterl (1), in each of 33 human incisors, calculated the mean numerical density of transversely sectioned dentin tubules along the central, long axis of the tooth near the dentin–enamel junction (DEJ), midway to the pulp, and near the pulp cavity. A centripetal increase in density was found through the three levels, ranging from 16,000 to 64,000/mm^2. His findings were questioned, and it was stated that the numerical density of cross-sectioned dentin tubules depended on their packing pattern and the thickness of intertubular dentin between them (2). In the monkey, rat, cat, and dog, represented by 26 teeth, tubular numerical densities did not differ much from human values. The values at DEJ and the pulp wall were not obtained from the same teeth within each species, however (3). According to a later report, the difference in tubular numerical density between peripheral and pulpal dentin was only slightly more than 100% (4). A study of tubule numbers per square millimeter and distances between adjacent tubules in teeth of man, the baboon, and the dog indicated that the values were specific for the three groups, and it was suggested that such dentin variables might be of taxonomic value (5).

Several authors have described the dimensions of peritubular dentin surrounding the odontoblast processes (6–10). It was suggested that peritubular dentin was secondarily produced by the odontoblast process and that, consequently, the diameter of peritubular dentin remained fairly constant from the DEJ to the pulp (10). This was not fully in agreement with a later report, in which it was stated that the diameter increases centripetally to half-way between the DEJ and the pulp and thence decreases (11). Variations in thickness of peritubular walls, independent of distance from pulp, were found within single teeth (12).

Except for Ketterl (1), no authors have indicated that they have attempted to follow a given bundle of dentin tubules from the DEJ to the pulp wall while measuring changes in numerical density and peritubular diameters within a single tooth. This may be one reason for the discrepancy between reported density values in peripheral and pulpal dentin. No authors have tried to quantify variation in central distances between cross-cut adjacent dentin tubules or variation in their distributional pattern within single sections or from the DEJ to the pulp in single teeth.

The main purpose of the present study was to determine in single teeth the numerical density and the distributional pattern of one bundle of dentin tubules transversely cut near the DEJ, midway to the pulp, and near the pulp wall in sections tangential to the imbrication lines, to calculate the mean area and diameter of peritubular dentin surrounding single tubules and the mean proportion of peritubular dentin in such sections and the variation of these dimensions within the sectional planes. The data obtained should indicate to what degree the secretory areas of single odontoblasts—that is, the dentin territories allotted each of them and their processes—are regularly distributed from the DEJ to the pulp.

To describe these variables, we used a method that had been developed for prismatic enamel (13).

Materials and methods

Eight upper premolars extracted for orthodontic reasons (patient age, 10–14 years) and stored in 4% formalin were used. With Gilling's Thin Sectioning Machine each tooth was sectioned axiobuccolingually, but slightly lateral to the longitudinal axis, to expose the central buccolingual plane in one of the two resulting halves. On this plane, in the coronal part, a guideline was engraved buccally, following the main course of a bundle of dentin tubules and crossing the DEJ approximately 3.5 mm from the cementoenamel junction. Across this line, parallel with the course of von Ebner's incremental lines near the guideline, were engraved two new sectioning lines in four of the eight teeth, one about 300 μm pulpal to the DEJ and one about 300 μm peripheral to the pulp wall. The total thickness of the dentin along the guideline was approximately the same in all teeth used (Fig. 1). In the remaining four teeth only one sectioning line midway between the DEJ and pulp, parallel with the incremental lines, was engraved across the guideline. The engraving technique has been described (14). The thickness of our cutting disk made it impossible to cut all three sections—peripheral, pulpal, *and* middle—from each single tooth. Approximately 50-μm-thick, centrally located longitudinal buccolingual ground sections of additional intact premolars from patients of the same age were made, to determine the angle between von Ebner's imbrication lines and the DEJ in the position where the guidelines were to be located in other specimens. The angles in all these sections were about 12°. Close and parallel to each sectioning line, normal to the engraved surface, cuts were made with Gilling's sectioning machine, slightly inside the peripheral and outside the pulpal line in the first four specimens. The resulting four pairs of tooth segments, each representing one of the first four specimens, were attached by the cut surfaces to ordinary microscope slides, using Eukit (O. Kindler, GmbH & Co., Freiburg, Germany) and ground down to a thickness of 50 μm (15). In the other four teeth two cuts were made, one on either side of the single, centrally located sectioning line. The resulting four

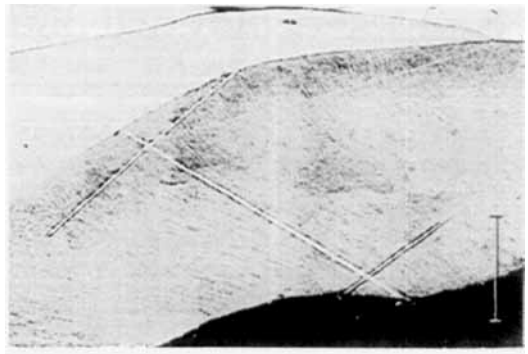

Fig. 1. Central axiobuccolingual plane of an upper premolar with engraved guideline along the course of the dentinal tubules. Crossing the guideline, two 'sectioning' lines, converging slightly cuspally, are aligned tangentially to the directions of the incremental lines crossing the guideline near the dentin–enamel junction and near the pulp. Along the sectioning lines the specimen will be cut to make ground sections transversal to the dentinal tubules. Etched 5 sec with 2.6% HNO_5. Toluidine blue. Montage. Bar represents 1000 μm.

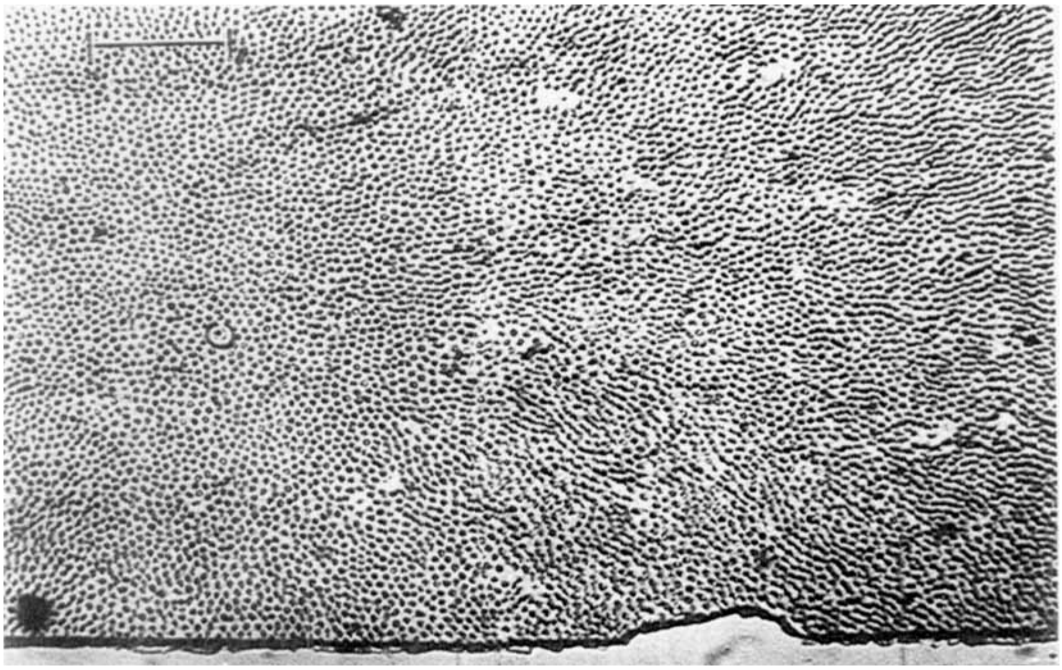

Fig. 2. Unetched and unstained ground section near the dentin–enamel junction tangential to the incremental lines near the guideline, which is seen as a notch below, in the axiobuccolingual plane (Fig. 1). The center of the area where the tubules are perpendicular to the section is marked by a *C*. It forms an island from which radiate in all directions rows of the progressively more obliquely cut tubules. Near the *C* the tubules seem to be arranged in curved rows with different orientations. Bar indicates direction of long axis of tooth, and its length represents 100 μm.

middle sections, each representing one tooth, were ground down on both sides to a thickness of 50 μm. The original guideline is seen as a notch in the straight border representing the axiobuccolingual sectioning plane. Near this notch the dentin tubules are cut transversely, forming an island in the center (C) of a pattern of progressively more obliquely cut tubules forming rows radiating in all directions (Fig. 2).

For the calculation of numerical density and distributional pattern of transversely cut dentin tubules a method developed for determing those variables in prismatic enamel was used (13, 16–18). This method will be briefly described.

In a regular distribution (closest packing pattern) of cross-cut dentinal tubules the numerical density—that is, their number per unit area—can either be found by counting within an area of known size and form, such as a parallelogram, or by triangulation. The first approach means that tubules within the area are counted (1). By the second approach the central distances between three adjacent tubules forming a triangle are measured. The sides of such a triangle are designated d, y, and x, d being the most horizontal side. Two triangles with one side in common form a tetragon. In a regular pattern there are as many such tetragons with common sides as there are tubules (13, 16–18). When the method is used on patterns of cross-cut tubules, the triangles with corners in adjacent tubules are far from congruent (Fig. 3). Therefore many triangles within a given irregular pattern have to be measured. By its area each triangle within a cluster of tubules describes a given numerical density (ND). From each measured triangle within a pattern, ND has been calculated. The value ND of each section is therefore

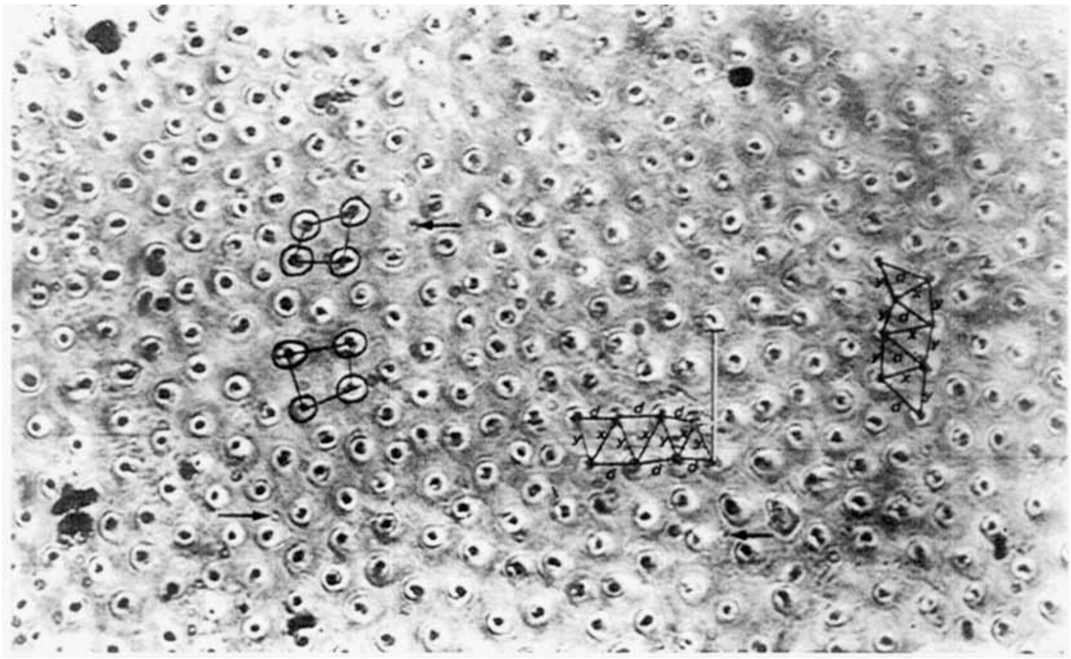

Fig. 3. Transversely cut tubules in 50-μm-thick, untreated, outer ground section. There are both vertical and horizontal rows. Two clusters of triangles have been traced. Each triangle has corners positioned in three adjacent tubules and the sides are designated *d, y,* and *x*, and *d* is the side most perpendicularly oriented to the long axis of the tooth. The left cluster represents a pattern in which *d* is horizontal, and the right a pattern in which *y* is vertical, analogous to prism distributions in enamel. The tooth axis is indicated by the magnification bar through the right corner of the left cluster. Two separate, isolated tetragons with corners positioned in four adjacent tubules have been traced at left. Surrounding each of these tubules, the borders of the peritubular dentin have been traced. In a given area of transversely cut tubules, there are theoretically as many adjacent tetragons with common sides as there are tubules. Therefore the mean area of them equals the mean dentin area allotted each productive odontoblast with a centrally located dentinal tubule. Some smaller, narrower tubules were seen between the ordinary ones (arrows). Bar represents 20 μm.

the mean of all the NDs of that section with a standard deviation (SD) describing the variation. For each section a mean central distance D and its SD can be expressed (13, 19).

Secretory odontoblast area, or odontoblast territory (OT), was also calculated. This is a territory surrounding a dentinal tubule and bordered by an imaginary line midway to all surrounding, adjacent tubules. It includes also intertubular dentin midway to adjacent odontoblast territories. OT would be difficult to define directly, but is the size of a tetragon with its corners in four neighboring tubules (19). It is accepted that each odontoblast produces one tubule with surrounding dentin. Since odontoblasts are closely apposed, the area of a tetragon is equal to OT (16, 19).

In this paper the parameter K, which describes distortion of a regular, closest packing pattern, has been omitted, since no systematic deformation of the packing of cross-cut dentinal tubules was observed at any level (13, 16–18, 20). In studies on fossil enamels, prism diameter, prism area, and the ratio between prism and ameloblast territory were introduced (16). In the present study such variables have also been used, designating instead dimensions and relations of peritubular dentin. Several peritubular contours, normally half the number of triangles, were traced to calculate mean area (PA) and mean diameter of peritubular den-

Table 1. Numerical density (ND), central distance (D), odontoblast territory (OT), peritubular diameter (PD), peritubular area (PA), and the PA/OT ratio of dentin tubules near the dentin–enamel junction (DEJ) and near the pulp wall (PULP) for specimens 1–4

	ND	D	OT	PD	PA	PA/OT
Sp. 1						
DEJ						
N	40	40	20	20	20	20
Mean	13,458	9.51	78.4	2.94	6.93	0.09
SD	3,722	1.23	15.6	0.36	1.64	0.03
Pulp						
N	40	40	20	20	20	20
Mean	40,297	5.42	24.4	2.78	6.12	0.27
SD	7,919	0.48	6.8	0.26	1.17	0.09
Sp. 2						
DEJ						
N	40	40	20	20	20	20
Mean	16,491	8.54	63.5	3.41	9.24	0.15
SD	3,922	1.00	10.9	0.32	1.74	0.03
Pulp						
N	40	40	20	20	20	20
Mean	56,354	4.57	17.8	3.10	7.60	0.44
SD	9,253	0.37	3.1	0.25	1.24	0.11
Sp. 3						
DEJ						
N	40	40	20	20	20	20
Mean	15,516	8.76	59.7	3.84	11.50	0.20
SD	3,361	0.88	9.7	0.32	2.27	0.04
Pulp						
N	40	40	20	20	20	20
Mean	47,234	5.00	20.0	3.14	7.82	0.41
SD	6,619	0.37	4.1	0.31	1.52	0.14
Sp. 4						
DEJ						
N	40	40	20	20	20	20
Mean	22,244	7.32	47.9	3.36	8.93	0.19
SD	4,678	0.77	8.4	0.33	1.71	0.05
Pulp						
N	40	40	20	20	20	20
Mean	61,586	4.39	16.3	3.35	8.88	0.56
SD	11,807	0.41	2.2	0.29	1.51	0.13

tin (PD). An equal number of tetragons was also traced to calculate the ratio between peritubular area (PA) and OT. The difference between directly measured tetragons and those calculated by the central distances was not significant for 11 of the 12 sections ($P > 0.5$), while for specimen 4 inner section it was ($P > 0.005$). In Tables 1 and 2 the OT values are the directly traced ones.

In three sections, within dentin areas of known size, the tubules were also counted directly. The maximum and minimum difference between calculated and counted value for these areas constituted 10.3% and 1.3%, respectively, of the calculated values (13).

Table 2. Numerical density (ND), central distance (D), odontoblast territory (OT), peritubular diameter (PD), peritubular area (PA), and the PA/OT ratio of dentin tubules midway between the dentin–enamel junction (DEJ) and the pulp wall (PULP) for specimens 5–8

	ND	D	OT	PD	PA	PA/OT
Sp. 5						
N	40	40	20	20	20	20
Mean	40,385	5.41	25.3	3.22	8.18	0.33
SD	7,565	0.49	3.8	0.25	1.30	0.06
Sp. 6						
N	40	40	20	20	20	20
Mean	41,395	5.36	24.9	3.17	7.98	0.32
SD	8,716	0.55	4.3	0.31	1.52	0.06
Sp. 7						
N	40	40	20	20	20	20
Mean	33,819	5.93	29.7	3.17	7.92	0.27
SD	6,687	0.62	4.7	0.24	1.22	0.66
Sp. 8						
N	40	40	20	20	20	20
Mean	43,177	5.23	24.6	3.39	9.12	0.38
SD	7,078	0.45	4.1	0.34	1.83	0.11

The variables of each of eight sections representing specimens 1–4 were calculated twice with different sets of triangles and traced peritubular areas. The results of the first and second selections showed that the reproducibility with triangulation maximally deviated by as much as 10,000 tubules near the pulp. In this test the highest density in the outer section and the lowest density in the inner section of any given tooth were still significantly different below the 0.1% level for both sets of triangles. For all three tested factors for all eight teeth the one-way analysis of variance gave identical results for either set of measurements of specimens 1–4.

Within each section represented by micrographs, 40 triangles, evenly spaced in 6–8 clusters, were measured. Linear magnification was constant and given by a micrograph of a Leitz micrometer scale. In Fig. 3 central distances forming two smaller clusters of such triangles are traced. The measurements were made on a digitizing graphics tablet (Kontron AMO3, Munich, Germany). For each triangle the variables *d*, *y*,

x and linear magnification were entered, and ND, D, OT, and K were computed directly by a spreadsheet on a personal computer. Peritubular dentin areas and directly measured tetragons were entered separately. The results are listed in Tables 1 and 2. Statistical analysis was carried out using the SPSS/PC+ V.3.0 (SPSS Inc., Chicago, Ill., USA) statistical computer package. Since the middle sections did not represent the same specimens as the sections close to the DEJ or pulp, all 12 sections were pooled and statistically treated as representing three given dentin levels in human premolars.

Light microscopic techniques were consistently used, since the exact magnification in SEM micrographs is not easily determined, and a distortion in one direction may occur.

Results

Apart from the different numerical densities of tubules in outer and inner sections and the wider tubular lumina in the latter, there was no visible difference in regularity of distribution between these different levels. The peritubular diameters seemed slightly smaller in the inner than in the outer sections. Isolated vertical and horizontal rows of tubules were seen in the packing pattern at low magnifications. A mosaic of such more or less curved rows are observed near the DEJ (Fig. 2) close to C, which designates the area where the tubules are sectioned perpendicularly. Such rows often consisted of 5 to 15 cross-cut tubules, their mutual interproximate distances seeming shorter than to tubules in adjacent rows or clusters.

Tables 1 and 2 list the numbers of triangles, the mean values, and the standard deviations of the variables for each specimen described in Materials and Methods.

The means and standard deviations of the pooled measurements of each surface for ND is shown in Fig. 4, for PD in Fig. 5, and for the PA/OT ratio in Fig. 6. Using one-way analysis of variance, a statistically significant difference was found for each of the three variables, with $p = 0.000$. When the Student–Newman–Keuls option was added, a statistically significant difference with $p = 0.05$ was found between each pair of surfaces for all three variables.

The D values of outer and inner surfaces and the dependent OT values (Table 1) were significantly different for each single specimen when using Student's t test. The ratios between outer and inner ND values were quite similar for them all—that is, 0.33, 0.29,

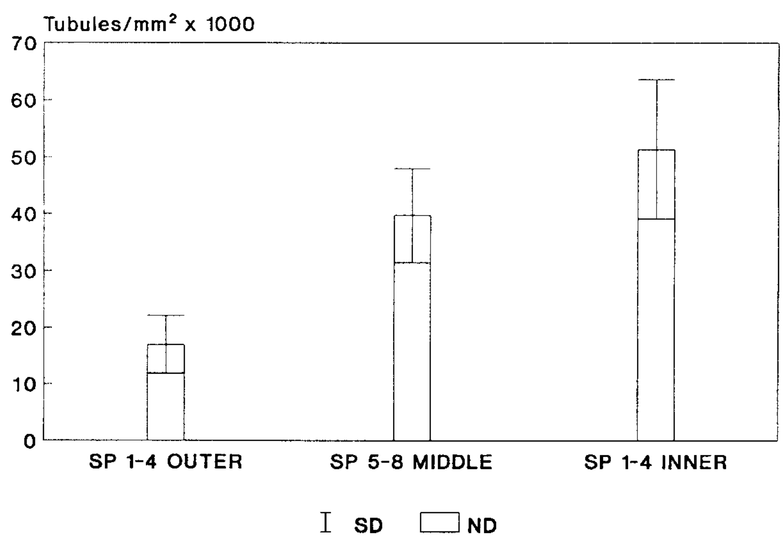

Fig. 4. Mean numerical density (ND) of dentin tubules on outer, middle, and inner surfaces of sectioned premolars.

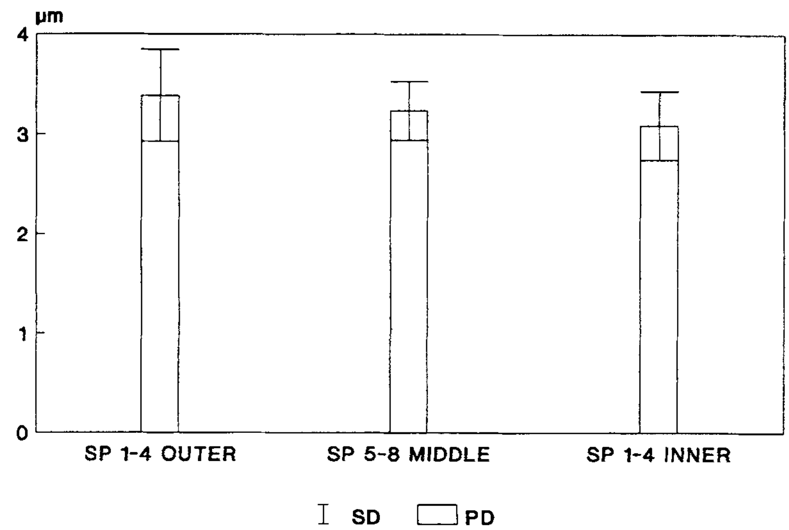

Fig. 5. Mean diameter of peritubular dentin (PD) on outer, middle, and inner surfaces of sectioned premolars.

0.33, and 0.36. On an average PD decreased centripetally by a factor of only 0.91 against an average factor of 0.57 for *D*. By definition, *D* is equivalent to the diameter of the mean odontoblast territory. The values PA/OT varied between the teeth, but the *ratios* between outer and inner PA/OT values were of similar magnitude: 0.33, 0.34, 0.48, and 0.33 for specimens 1, 2, 3, and 4, respectively—that is, nearly equal to the ND ratios—because the reduction of PD from DEJ to pulp was far smaller than for *D*. The values above quantify the pulpward decrease of intertubular dentin.

The ND and PA/OT values of the middle sections of specimens 5, 6, and 8 are all higher than the inner value of specimen 1 in Table 1. Apart from this latter section, all four ND and PA/OT values in Table 2 are higher than those of the outer sections and lower than those of the inner sections in Table 1 (see also Figs. 4 and 6), thus demon-

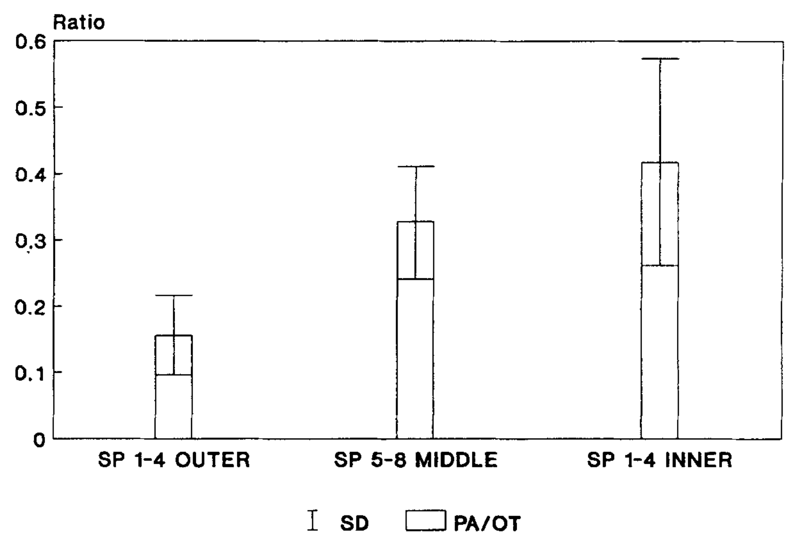

Fig. 6. Mean ratio between peritubular area and odontoblast territory (PA/OT) on outer, middle, and inner surfaces of sectioned premolars.

strating the gradual increase pulpally for both variables. It is remarkable, however, that the increase of ND from DEJ to midway in the dentin was much greater than from the latter position to the pulp (Fig. 4 and Tables 1 and 2).

Discussion

Even though the tissues are fundamentally different ontogenetically, quantitative comparisons between dentinal tubules and prisms are relevant, since it is accepted that each dentin tubule and each prism are produced by one cell. Odontoblasts and ameloblasts are closely apposed cells. In enamel of higher mammalian taxa the distributional pattern of transversely cut prisms is usually rather regularly hexagonal and may often be categorized in a pattern 2 or 3. Such patterns may be specific for different taxa (18, 21, 22). After the description of gigantoprismatic enamel in fossil multituberculate teeth (23–25) the method has been recently used in paleontology and archeology to test its taxonomic value (16–19, 26). It was hoped that the method, apart from describing distributional patterns of dentin tubules in different locations within single human teeth, might be used to demonstrate characteristics in distribution of dentin tubules in different taxa (5). Since variation in different variables is expressed, statistical comparisons are made possible. Moreover, reproducibility seems acceptable, since the two sets of measurements in the eight sections representing specimens 1–4 both indicated the same relation between the three dentin levels in the eight teeth for ND, PD, and PA/OT.

If central distances between prisms and tubules reflect diameters of productive territories of ameloblasts and odontoblasts, respectively, these territories of odontoblasts at the beginning of dentin formation are far larger than those of the ameloblasts at the beginning of enamel formation. In approximately the same position in enamel (position 2) of human permanent canines as that of our dentin measurements, the ameloblasts have a mean diameter (D) of 5 μm near the DEJ (14), as opposed to a mean D of 8.5 μm for the odontoblasts 300 μm from the DEJ (Table 1). At the end of the amelogenesis in that position the diameter of ameloblasts had increased to 6 μm, as opposed to a decrease to 4.8 μm for odontoblasts 300 μm from the pulp wall. The odontoblasts have then advanced about 2.3 mm pulpward, whereas the ameloblasts have advanced only 0.8 mm centrifugally.

Even though the distances between the outer and inner sections in the present study were not exactly the same in the four teeth, there was a distinct similarity of the ratios between outer and inner ND values. Moreover, the separate values for numerical density near the DEJ and near the pulp agree with the results of other authors (1–3, 5). The finding that the difference between ND near the DEJ and midway to pulp was considerably greater than that between the pulp and midway to the DEJ was not in accord with the results of Ketterl, who had counted along the tooth axis in incisors (1).

The diameter of enamel prisms decreases centripetally, as do the central distances. The central distances between tubular lumina in dentin also decrease in a pulpal direction, but it has been claimed that the diameters of peritubular dentin remain the same from the DEJ to the pulp (10) and that the diameter of peritubular walls was greatest half-way from the DEJ to pulp (11). In all specimens studied we found that the mean peritubular diameter and area decreased regularly through the three levels from the DEJ to the pulp. This decrease was slight but was statistically significant for the pooled eight teeth. On an average, the ratio between peritubular, cross-sectional area and productive odontoblast territory (PA/OT) increased from 0.15 via 0.32 to 0.42. These ratios quantify the pulpward decrease of intertubular dentin and substantiate the observation that the pulpward increase of dentin tubules occurs at the expense of intertubular dentin (10, 11).

The pulpward increase in numerical density of dentin tubules has been described (1–5), but direct comparisons with the ratio between outer and inner dentin surfaces in one tooth have not been carried out, as far as we know. That has been done for prism densities and surfaces of the enamel mantle of human teeth, and they corresponded fairly well (27). In dentin the ratio between inner and outer tubular densities was about 4 (1, 3). We found a mean ratio of only 3, however, between inner and outer density values (Table 1), but then our sections were not less than 300 μm inside the DEJ or outside the pulp wall.

As expected, for transversely sectioned dentin tubules there is no such orderly regularity as encountered for prisms in mammalian enamels, and rows are short, isolated, and without consistent orientation in dentin. Still, the relatively constant magnitude of central distances between tubules within each section from the DEJ to the pulp was remarkable, considering the crowding of odontoblasts, in contradistinction to the ameloblast layer, which expands during amelogenesis. The variation of D in dentin was not much greater than of D in enamel; that is, SD constitutes 9.7% of D in dentin and 8.14% of D in enamel (14). As the odontoblasts become crowded in the crown while the pulp cavity decreases in volume, it is not a matter of course that the territories surrounding the odontoblast processes of the more deeply situated perikarya should remain equal in size to those belonging to odontoblasts adjacent to the pulp wall.

In this study it was quantitatively confirmed that there is no systematic pattern in distribution of dentin tubules near the DEJ or close to the pulp and that in spite of the crowding of odontoblasts in several layers in the crown during dentinogenesis, the size of their secretory territories remains uniform at each level throughout the dentin thickness. A pulpward decrease in the width of peritubular dentin was also quantified, as was the increase of the ratio between peritubular area and secretory odontoblast territory, which includes intertubular dentin.

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Received for publication 13 November 1991