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THE FINE STRUCTURE OF HUMAN CEMENTUM

by

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INTRODUCTION

Several reports on the ultrastructure of human cementum and alveolar bone have been published in recent years (1, 2, 4, 8, 12, 13). It has been established that cementum, like bone and dentin, contains hydroxyapatite crystals which are deposited with their c axes parallel to the collagen fibrils of the organic matrix. The similarity in histological appearance of the cementum and alveolar bone which has been pointed out in many investigations by optical microscopy, has also been commented on in recent electron microscopic studies (4, 12).

The early development of dental root tissues has been studied electron microscopically in rodent incisors (28, 34). The collagen fibrils in the first cementum layer on these teeth form an irregular network without preferentially oriented, embedded periodontal fibers (Sharpey's fibers) (28).

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However, *Stern* (34) observed that collagen fibers from the periodontal membrane extended deeply into mature incisor cementum. *Selvig* (29) demonstrated that in areas where cementum was being deposited the surface was characterized by small, calcified projections corresponding to the insertion of each collagen fibril, indicating that deposition of mineral crystals on and within fibrils precedes the deposition between them.

The course of the Sharpey's fibers within human cementum has mainly been investigated by polarized light microscopy of decalcified sections (5, 11, 25, 26). Although cementum has not been studied extensively by microradiography, uncalcified or partly calcified channels which could be interpreted as Sharpey's fibers have been observed by this technique (32, 39).

In the electron microscope Sharpey's fibers of human cementum and alveolar bone have been observed in decalcified sections (12) and undecalcified material (4, 8) as well as by the replica technique (2). *Frank, Lindemann & Vedrine* (8) found that these fibers were uncalcified in alveolar bone, and *Dreyfuss & Frank* (4) reported that most Sharpey's fibers in human cementum also were uncalcified. *Selvig* (29), on the other hand, observed that in molars of young mice the mineral crystals were distributed almost homogeneously throughout the cementum, and the Sharpey's fibers were as calcified as the rest of the matrix.

The purposes of the present investigation are to study whether acellular and cellular human cementum are ultrastructurally similar to, or different from alveolar bone, to determine by electron microscopy if the Sharpey's fibers in the human periodontium are uncalcified, partly calcified, or completely calcified, and to compare the results with those derived from the observation of ground sections and microradiographs of the same specimens.

MATERIALS AND METHODS

Freshly extracted teeth were obtained from individuals of different ages. Some teeth were removed by a surgical procedure with an attached, intact portion of the periodontal membrane and alveolar bone.

Most specimens were fixed in a buffered osmium tetroxide solution. Others were fixed in formalin, to permit examination of the soft tissues by transmitted and polarized light. The specimens were embedded in polyester resin or methacrylate mixtures, and serial ground sections in the thickness range of 30 to 100 microns were prepared at right angles to or parallel to the long axes of the teeth.

Contact microradiographs of the ground sections were routinely made with Ni-filtered Cu Kα radiation (wavelength 1.54 Å). In order to demonstrate finer structural details some sections were ground by hand to a thickness of 10 to 20 microns, and contact microradiographs were made with unfiltered Al or Ti radiation (Kα wavelength 8.34 Å and 2.75 Å, respectively) emitted at 15 kV from a multi-target X-ray tube ([38]). To insure good contact between the sections and the fine-grained emulsion a specially designed vacuum cassette ([27]) was used.

Silver-shadowed negative collodion replicas for optical microscopy were obtained from the surfaces of a few ground sections, after etching of the sections by immersion in 0.1 N HCl for 20 seconds.

After microscopic examination of the ground sections and corresponding microradiographs, regions of acellular cementum, cellular cementum, and alveolar bone were dissected from the ground sections and re-embedded in methacrylate for electron microscopy. Regions of the cementum which demonstrated resorption, hypercementosis, or other indications of irregular deposition were avoided. Thin sections cut with diamond knives were examined in the electron microscope either without additional staining or after staining by flotation on a saturated solution of uranium acetate in 50 per cent alcohol. Decalcification of the sections was carried out by floating the grids on 2 per cent phosphotungstic acid for 30 minutes.

The electron microscope was operated at 80 or 100 kV and micrographs were obtained at original magnifications up to 40,000 diameters. Selected area diffraction patterns were obtained in the electron microscope from areas approximately 1 micron in diameter.

RESULTS

Acellular cementum

When the ground sections were examined by transmitted light, the thin, acellular cementum in general appeared as a finely lamellated tissue, characterized by numerous incremental lines running parallel to the root surface. Near the cemento-dentinal junction the acellular cementum regularly contained a zone of radially oriented fibrous structures. The width of this zone was in some sections only ten to fifteen microns, in others up to fifty microns. The cementum surface appeared as a smooth line (Figure 1).

In the microradiographs the innermost layer of cementum appeared less X-ray dense than the more peripheral layers, indicating a lower mineral content. Within this zone thin, radially oriented, radiolucent structures could be seen. The outer layers of the acellular cementum exhibited an almost homogeneous X-ray density, although more radiopaque incremental lines occasionally were present (Figure 2).

Radially oriented structures which could be interpreted as embedded periodontal fibers were not regularly observed in acellular cementum, except in the zone nearest to the cemento-dentinal junction. However, the presence of such fibers in all layers of the tissue could easily be demonstrated by polarized light microscopy or by the replica technique (Figure 3).

When observed in the electron microscope the acellular cementum had a very regular appearance which varied little from one specimen to another. Bundles of densely packed fibrils, arranged more or less a right angles to the root surface, were inserted into the cementum along most of the surface (Figure 4). The cementum surface in these areas, which in the optical microscope and at low magnifications in the electron microscope formed a more or less straight line, was at higher magnifications characterized by a serrated appearance due to protruding pyramids of calcified tissue. Each projection corresponded to the insertion of one collagen fibril (Figure 5). In other areas the acellular cementum appeared to incorporate fibrils which were more irregularly arranged or were oriented parallel to the sur-

face and, therefore, probably did not take part in the attachment of the tooth (Figure 6). In these areas the calcified tissue had a less regular surface than described above. The nearest cells of the periodontal membrane were generally separated from the calcifying cementum by a three to five-micron wide zone of precementum containing densely packed collagen fibrils (Figure 7).

Since the crystals in general were deposited parallel to the collagen fibrils, the course of the fibrils could be followed into the calcified tissue without decalcification of the sections. Figure 8 illustrates a section where the mineral crystals were radially oriented. Selected area diffraction patterns indicated a high degree of preferred orientation of the crystals in such regions. The collagen seemed to form wide sheets of parallel fibrils. Although the thin, acellular cementum in some specimens contained regions where bundles of fibrils were arranged parallel to the root surface, the impression remained that the fibrils more often were oriented radially throughout the tissue.

The deepest layer of cementum, corresponding to the radiolucent zone that was demonstrated microradiographically, frequently contained bundles of fibrils which were less densely mineralized than the rest of the matrix (Figure 9), or even contained localized areas which were free of mineral (Figure 10). These bundles were oriented more or less at right angles to the cemento-dentinal junction. The width of the uncalcified or partly calcified spaces was of the order of one or two microns, and sometimes more. Uncalcified spaces were only rarely observed in peripheral layers of the tissue. Thus, except in the inner zone, the mineral crystals were almost homogeneously distributed throughout the acellular cementum (Figure 8).

Cellular cementum

When examined either directly in the optical microscope or by means of microradiography, ground sections of cellular cementum presented a more varied appearance than did the acellular tissue. Cellular cementum was in general less radiopaque than the acellular variety. Layers of cellular cementum were separated by X-ray dense resting lines or by layers of acellular

cementum. Sharpey's fibers could regularly be identified in the ground sections, both at the surface and in deeper layers of the tissue (Figure 11). They could also be recognized as radiolucent lines in corresponding microradiographs (Figure 12), although less consistently than in the ground sections. Thus, it appeared that only in some regions of cellular cementum the Sharpey's fibers formed uncalcified channels of sufficient width to be detected by the microradiographic technique used. The uncalcified channels within one layer of cementum were frequently continuous with those of adjacent layers, but seemed to be less wide where they passed an incremental line. The width of these structures was one to two microns, occasionally up to five microns (Figure 13).

In addition to the embedded periodontal fibers, other structures which formed more or less radially oriented channels in the cellular cementum were frequently present. These structures included accessory root canals, spaces presumably containing entrapped soft tissue elements, and canaliculi extending from the lacunae of the cementocytes. In the optical microscope these structures did not represent any problems of differentiation.

In the electron microscope the surface of cellular cementum frequently had a different appearance from that of acellular cementum. The precementum zone contained an irregular meshwork of single collagen fibrils and bundles of fibrils. Calcification foci could be observed in this zone separate from the continuous part of the cementum. The cementum seemed to increase in thickness partly by apposition of minerals on the surface of the calcified tissue and partly by incorporating the already calcified foci (Figure 14).

Principal fibers of the periodontal membrane were inserted into the cementum as Sharpey's fibers at varying intervals along the surface. In some areas mineral crystallites were found as densely packed within these fibers as in the interjacent areas of the matrix, while in other areas Sharpey's fibers which were not completely calcified could be traced into the calcified tissue.

Differences in the mineral content of Sharpey's fibers compared with the mineral content of the surrounding matrix were also observed in deeper layers of cellular cementum. When thin,

tangential sections were made through this tissue the Sharpey's fibers appeared as distinct, more or less circular structures separated from each other by calcified tissue containing more randomly arranged fibers (Figure 15). The Sharpey's fibers consisted of an uncalcified, irregularly shaped central core, surrounded by a highly calcified peripheral part. Densely packed collagen fibrils were present in the central as well as in the peripheral portions of the fibers (Figure 16). The collagen fibrils almost filled the uncalcified regions leaving little interfibrillar space. There was an abrupt transition between the uncalcified and calcified portions of the Sharpey's fibers, rather than a gradual increase in mineralization from the center toward the periphery of the fibers. When thin sections were decalcified and stained with phosphotungstic acid, the uncalcified core of the Sharpey's fibers appeared more darkly stained than the peripheral portions of these fibers and the surrounding matrix (Figure 17). Most Sharpey's fibers were less than 10 microns in diameter, while the width of their uncalcified core was of the order of one to two microns (Figure 15), but sometimes five microns or more (Figure 17). In some regions of cellular cementum the Sharpey's fibers were completely or almost completely calcified.

The cellular cementum also contained fibers of varying diameter running parallel to the surface. Some of these fibers were of approximately the same width as the Sharpey's fibers. Several such fibers were often oriented parallel to each other at certain intervals (Figure 18). These fibers were completely and homogeneously calcified.

The hydroxyapatite crystals at the surface of acellular and cellular cementum appeared as thin, platelike structures with dimensions not larger than $400 \times 200 \times 20$ Å (Figure 19). They seemed to grow rapidly in size with increasing distance from the surface, and reached their maximum size within a few microns from the calcification front (Figures 20 and 21). The thickness of the mature crystals seemed to be fairly constant, around 80 Å, while their length and width showed greater variations (Figure 20). The width of the zone of increasing crystal size was often difficult to evaluate, but in those sections where it could be estimated it varied from one to two microns, and occasionally reached four microns.

Alveolar bone

Ground sections of alveolar bone always contained uncalcified structures extending from the periodontal membrane into the hard tissue, indicating the location of embedded periodontal fibers. The uncalcified channels had a width similar to those of the Sharpey's fibers in cellular cementum. The distance between the insertion of adjacent fibers within any plane of focus in the ground sections was 10 to 30 microns. These structures were also recorded in corresponding microradiographs (Figures 22 and 23).

The Sharpey's fibers which were seen by optical microscopy could be readily identified in electron micrographs (Figure 24). They consisted of bundles of parallel collagen fibrils inserted into the bone at varying intervals. At somewhat higher magnifications, the Sharpey's fibers in bone, like those in cellular cementum, were seen to contain an uncalcified core of collagen fibrils, surrounded by a peripheral layer where the crystallites seemed to be at least as densely packed as in the surrounding matrix.

When the alveolar bone was sectioned parallel to its periodontal surface the Sharpey's fibers appeared as more or less circular structures, similar to those seen in cellular cementum. While most Sharpey's fibers contained an uncalcified core, some fibers seemed to be completely calcified (Figures 25 and 26). The diameters of the Sharpey's fibers varied within wide limits. Most of them were less than 10 microns in width, but diameters of 20 microns or more were sometimes observed (Figure 26). Selected area electron diffraction patterns indicated that the hydroxyapatite crystals within these fibers were oriented with their c axes parallel to the collagen fibrils and to the fiber itself, but randomly arranged about this axis (Figures 27 and 28).

The calcified tissue between the embedded periodontal fibers contained layers of fibers which were oriented parallel to the surface of the bone, as well as large regions where the matrix fibrils seemed to be randomly arranged. Thin bundles of fibrils frequently entwined the Sharpey's fibers (Figure 25). When tangential sections through the calcifying bone surface were examined the calcification process often appeared to be more advanced

between the embedded periodontal fibers than within them (Figure 29).

Lacunae containing cell bodies were present in greater number in alveolar bone than in cellular cementum. The uncalcified canaliculi could easily be differentiated from the partly calcified Sharpey's fibers by their regular, circular appearance in cross sections and by the different appearance of the uncalcified contents of these structures (Figure 30). Also, the collagen fibrils, as well as the mineral crystals, were oriented parallel to the cores of the Sharpey's fibers, while matrix fibrils surrounding the canaliculi did not exhibit such orientation.

In all regions along the bone surface where fibrils were inserting into the calcified tissue the apatite crystals appeared as very small, thin, platelike structures with the same dimensions as those found on the surface of cementum (Figure 31). The crystals seemed to reach the size of mature crystals within one to three microns from the surface. Crystals bordering on uncalcified spaces in the deep layers of the tissue, such as lacunae, canaliculi, and the uncalcified cores of the Sharpey's fibers, were found to resemble the mature apatite crystals in size (Figure 32).

DISCUSSION

The present report supports the statement by *Herting* (12) that no regions of the intercellular cementum matrix are free of collagen. The collagen fibrils of the cementum and alveolar bone matrix can be divided into two groups which differ in development and appearance.

The first group consists of the principal fibers of the periodontal membrane, which can be traced from the periodontal membrane through the precementum or osteoid layer and into the calcified tissue, where they are recognized as Sharpey's fibers. These fibers are formed by fibroblasts in the periodontal membrane, and gradually become embedded in the cementum or bone as more calcified tissue is laid down. In other bones of the body as well the Sharpey's fibers represent originally extra-osseous collagen bundles which have been included within the bone during its growth (31).

The second group of collagen fibrils fills the space between

the embedded periodontal fibers. These fibrils form a dense meshwork in the precementum and osteoid layers and presumably are produced by cementoblasts and osteoblasts.

The acellular cementum of human teeth contains mostly radially oriented fibers, as demonstrated by polarized light microscopy [5, 25] and electron microscopy [12]. These fibers belong to the first group. This type of cementum, therefore, seems to serve the primary purpose of anchoring the tooth in its alveolus. In the cellular cementum and alveolar bone, on the other hand, the Sharpey's fibers constitute only a portion of the collagen fibrils which make up the matrix. Most fibrils and bundles of fibrils are not directly engaged in attachment of the tooth but serve other functions within the tissue. The width of the Sharpey's fibers in alveolar bone seems to be similar to the width of such fibers in tibia and femur [31].

Sharpey's fibers could not generally be identified in microradiographs of acellular cementum. Electron microscopy of such tissue demonstrated that these fibers were indistinguishable from other fibers of the cementum matrix on the basis of difference in mineralization, and that they, in fact, made up most of the matrix in this tissue. In alveolar bone and cellular cementum, on the other hand, the Sharpey's fibers formed distinct structures within the calcified tissue. The fibers were either completely calcified or consisted of an uncalcified core surrounded by a highly calcified peripheral part. Thus, the uncalcified structures often observed in microradiographs and dried ground sections of cementum must represent the uncalcified core of the Sharpey's fibers rather than the whole fiber.

Some interest has recently been focused on the interpretation of microradiographic images of fine structural details in ground sections of teeth [9, 22]. *Glas & Nylen* [9] demonstrated that microstructures which fall below the limit of resolution inherent in the microradiographic technique can be recorded because of a summation effect if several such structures are superimposed in the section. Since the Sharpey's fibers within any small region of cellular cementum or alveolar bone are arranged more or less parallel to each other the radiolucent image of these fibers in the microradiographs may well represent the image of two or more uncalcified channels in the path of the X rays. Such con-

siderations may explain how these 1 to 5-micron wide structures sometimes can be demonstrated in microradiographs of ground sections which are 50 microns or more in thickness.

The radiolucency of the innermost layer of cementum can be explained as a summation effect due to overlapping in the ground sections of the many partly calcified radial fibers which were demonstrated within this layer.

The reason why the central cores of the Sharpey's fibers within bone and certain regions of cementum often remained uncalcified, while other matrix fibers of the same diameter calcified completely, is not clear. The explanation must probably be sought in the difference in development of these fibers. Since Sharpey's fibers are derived from periodontal fibers, which are not calcifiable in their original location, it seems reasonable that these fibers will calcify after they have become embedded in bone and cementum only if they have acquired the concentration of inorganic ions and ground substance components required for calcification, and if possible inhibiting substances have been removed. This exchange must take place in the precementum and osteoid zones, and would be most complete in regions where hard tissue formation was proceeding at a slow rate, such as during formation of acellular cementum. In regions where the hard tissue deposition is rapid and the fibers wide, such as on the surface of alveolar bone, the exchange of material may not be completed before the fibers become embedded and, thus, will leave uncalcifiable cores in the fibers.

This suggestion is also supported by the observation that the Sharpey's fibers remained uncalcified in deep layers of the tissue, and by the observation that all uncalcifiable fibers were radially oriented, embedded periodontal fibers (Sharpey's fibers), while fibers which most likely had been formed in the precementum and osteoid zones were completely calcified even though they were often as wide as the embedded periodontal fibers. Additional evidence that the fibers were not undergoing calcification is provided by the observations that there was an abrupt change in mineral content between the core and the periphery of the fibers, and that the uncalcified spaces were bordered by apatite crystals of mature size rather than by small crystals such as found at the calcification front.

The hydroxyapatite crystals in mature cementum and alveolar bone were considerably larger than those found at the calcification front. Such differences have also been suggested by investigations on other bones and on dentin [23, 24, 35]. In sections where it could be determined the zone of increasing crystal size below the bone and cementum surface was one to four microns in width. The width of this zone is probably related to the rate at which the calcified tissue is deposited and would, therefore, be expected to vary greatly in different locations. *Zander & Hürzeler* [40] found that the deposition of cementum in general occurred at a linear rate throughout the life of the individual. The rate of deposition was higher in the middle region than in the cervical region of the root, and highest in the apical region. The presence of incremental lines together with the observation that the incremental layers form patches on the root surface rather than continuous layers around the root [25] has been thought to indicate an intermittent rather than a continuous deposition.

The observation that all specimens in the present study contained a zone of very small mineral crystals at the cementum surface tends to support the concept that cementum is formed continuously. This does not preclude, however, that the rate of formation may vary greatly with time and from one region to another.

The surface layer of cementum has been reported to be more highly X-ray dense than subjacent layers [7, 14, 19, 30]. In view of the continuous nature of cementum formation interpretation of these observations is controversial. As demonstrated by *Selvig & Zander* [30], secondary mineralization of the cementum surface may take place in areas which have been exposed to the oral cavity because of periodontal disease. A relative difference in mineralization will also be observed if the tooth is extracted at a time when an incremental line or resting line is being formed. These factors should be kept in mind when microradiographs of cementum are interpreted.

When the position of the tooth in the jaw changes due to eruption, orthodontic, physiologic or pathologic tooth movement, the periodontal fibers rearrange and new layers of bone and cementum may contain embedded fibers that are oriented at different angles to the surface than in deeper layers [5, 11, 25]. The

same fiber can be traced through several layers of calcified tissue. This indicates that the deposition of new hard tissue serves the purpose of providing a continuous attachment of the cementum to the existing periodontal fibers.

The total amount of cementum formed on the root during life of the individual is of the order of a few hundred microns. Since the embedded fibers in the cementum are partially or completely calcified, it is difficult to conceive of any significant turnover of the collagen in these fibers. If there is any turnover, it must occur as a molecular rearrangement rather than as new fiber formation. The bony wall of the alveolus, on the other hand, constantly undergoes remodeling by resorption and new bone formation, through which new fibers become embedded in the calcified tissue. Autoradiographic investigations utilizing labelled collagen precursors have demonstrated more active collagen formation on the surface of alveolar bone than on the cementum surface (3, 33). This tends to indicate that the collagen turnover rate is higher than on the cementum side. Other experimental evidence also supports this conclusion. Thus, during protein deprivation the alveolar fibers become lost and bone is resorbed while the fibers from the cementum still remain despite the deficiency of protein essential for collagen formation, again suggesting that the turnover of collagen in cementum may be slower than on the alveolar side of the periodontal membrane (10). Similar findings also accompanied experimentally induced ascorbic acid deficiency (37). Investigations on other collagens have demonstrated age changes in this fibrous protein, such as increasing insolubility in cold, weak salt solution with age (15), increasing orientation on a molecular level (6), increasing resistance to certain types of swellings (17, 18) and to enzymatic digestion (16), and increasing resistance to metabolic turnover (20, 21).

To summarize, the observations referred to above, together with those presented in this report, indicate that the embedded portions of the periodontal fibers, particularly those in the cementum, serve functional purposes over a long period of time, and also suggest that these fibers will become more inert with age. Rearrangement of the periodontal fibers following changes in tooth position must, therefore, to a great extent be accounted for by changes within the periodontal membrane rather than at

the bone or cementum surface. The presence of an intermediate plexus has been refuted by several recent histological studies [3, 36]. However, it seems reasonable that a gradual rebuilding of the collagen fibers can take place without presupposing the presence of a distinctive, histologically recognizable intermediate plexus. The turnover of collagen in the periodontal tissues deserves further study at the histological as well as the ultrastructural level utilizing labelled collagen precursors.

SUMMARY AND CONCLUSIONS

The attachment of periodontal fibers to human cementum has been studied by optical microscopy, microradiography, and electron microscopy, and compared with the attachment of these fibers to the alveolar bone.

When the ultrastructure of acellular cementum was compared with that of cellular cementum and alveolar bone, differences were found in orientation, width, and degree of calcification of the matrix fibers.

The embedded periodontal fibers (Sharpey's fibers) in acellular cementum were closely packed and, in general, completely calcified, like those of young mouse molar cementum which has been described previously. Only in a 10 to 50-micron wide zone near the cemento-dentinal junction were partly calcified fibers regularly present, explaining the radiolucent zone observed in this region of cementum.

In human cellular cementum and alveolar bone the Sharpey's fibers were separated by other fibers oriented parallel to the surface of the hard tissue or by randomly arranged fibers. The Sharpey's fibers, which were up to 20 microns in width, consisted of a one to five-micron wide uncalcified core surrounded by a highly calcified peripheral zone. However, in some regions of cellular cementum most Sharpey's fibers were completely calcified. Thus, the uncalcified fibrous structures which have often been described in dried ground sections and in microradiographs represent the uncalcified cores of the Sharpey's fibers rather than the whole fibers.

The hydroxyapatite crystals at the calcification front of cementum and alveolar bone appeared as thin, platelike structures.

They seemed to reach their mature size within a few microns from the surface. The presence of small, immature crystals on the surface of the cementum in all specimens in this study supports the concept that cementum is formed continuously.

RÉSUMÉ

LA FINE STRUCTURE DU CÉMENT HUMAIN

L'attachement des fibres desmodontales au cément humain a été étudié par microscopie optique, microradiographie et par microscopie électronique, et comparé à l'attachement de ces fibres à l'os alvéolaire.

Lorsqu'on comparait l'ultrastructure de cément acellulaire à celle du cément cellulaire et de l'os alvéolaire, on observait des différences dans l'orientation, la largeur et le degré de calcification des fibres de la matrice.

Les fibres desmodontales noyées (fibres de Sharpey) dans le cément acellulaire étaient serrées les unes contre les autres et, en général, entièrement calcifiées, comme celles du cément de molaire de jeunes souris décrit antérieurement. Ce n'est que sur une zone de 10 à 50 microns de largeur près de la jonction cémento-dentinaire que des fibres partiellement calcifiées étaient régulièrement présentes, ce qui explique la zone radioclaire observée dans cette région du cément.

Dans le cément cellulaire et l'os alvéolaire humains, les fibres de Sharpey étaient séparées par d'autres fibres orientées parallèlement à la surface du tissu dur et par des fibres disposées au hasard. Les fibres de Sharpey, qui avaient une largeur allant jusqu'à 20 microns, consistaient en une partie centrale d'une largeur de un à cinq microns, non calcifiée, et entourée d'une zone périphérique fortement calcifiée. Cependant, dans quelques régions du cément cellulaire, la plupart des fibres de Sharpey étaient entièrement calcifiées. Ainsi, les formations fibreuses non calcifiées qui ont été souvent décrites dans les coupes sèches par usure et polissage et dans les microradiographies représentent la partie centrale non calcifiée des fibres de Sharpey plutôt que les fibres entières.

Les cristaux d'hydroxy-apatite au niveau du front de calcification du cément et de l'os alvéolaire se présentent comme des for-

mations minces, en forme de plaques. Ils semblent atteindre leur taille de maturité en l'espace de quelques microns à partir de la surface. La présence, sur la surface du cément dans tous les spécimens de cette étude, de petits cristaux n'ayant pas atteint leur maturité confirme la théorie suivant laquelle le cément se forme continuellement.

ZUSAMMENFASSUNG

DIE FEINSTRUKTUR DES MENSCHLICHEN ZAHNWURZELZEMENTES

Die Befestigung der periodontalen Fasern zu dem menschlichen Zahnwurzelzement wurde sowohl lichtmikroskopisch als mikroröntgenographisch und elektronenmikroskopisch untersucht, und mit der Befestigung dieser Fasern zu dem Alveolarknochen in Vergleich gestellt.

Wenn die Ultrastruktur des zellfreien Zementes mit der des zellhaltigen Zementes und des Knochengewebes verglichen wurde, konnten Unterschiede in Verlaufsrichtung und Dicke und auch in Verkalkungsgrad der Fasern der organischen Matrix nachgewiesen werden.

Die periodontalen Fasern (Sharpeysche Fasern) des zellfreien Zementes waren dicht zusammengepackt und meistens durchaus verkalkt, in derselben Weise wie die des schon vorher beschriebenen Zementes der Molaren junger Mäuse. Nur in einer 10 μ bis 15 μ breiten Zone nahe der Zementdentingrenze war es möglich unvollständig mineralisierte Fasern stetig nachzuweisen, die zur Erklärung der röntgentransluzenten Zone dieses Zementbereiches dienen konnte.

In dem menschlichen zellhaltigen Zement und im Alveolarknochen waren die Sharpeyschen Fasern durch andere Fasern zerteilt, deren Richtung parallel zur Oberfläche des mineralisierten Gewebes war, oder auch von Fasern deren Richtung mehr zufällig erschien. Die Sharpeyschen Fasern, deren Durchmesser bis 20 μ betrug, bestanden aus einem bis 5 μ weiten unverkalkten Kern, der von einer stark mineralisierten oberflächlichen Zone umgegeben war. In einigen Bezirken des zellhaltigen Zementes aber waren die Sharpeyschen Fasern meistens vollständig verkalkt. Deshalb sind die unverkalkten Faserstrukturen, die gewöhnlich in Dünnschliffe und Mikroröntgenogrammen beschrie-

ben worden sind, als Wiedergabe des unverkalkten Kernes und nicht der ganzen Fasern anzusehen.

Die Hydroxylapatitkristallen der ersten Mineralisationszone des Zementes und des Alveolarknochens erschienen als dünne, plattenförmige Strukturen. Scheinbar erreichten sie ihre volle Grösse binnen weniger Mikrons Entfernung von der Oberfläche.

Das Vorhandensein kleiner unreifen Kristallen an der Oberfläche des Zementes aller untersuchten Präparaten müssen die Auffassung unterstützen, dass das Zahnwurzelzement kontinuierlich gebildet wird.

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PLATES

Figure 1 Ground section of acellular cementum observed by transmitted light. Numerous incremental lines run parallel to the root surface. Near the cementodentinal junction the cementum contains a zone of radially oriented fibrous structures. C-cementum, D-dentin. Cross section from the middle root region of an upper lateral incisor. ×160.

Figure 2 Microradiograph of the same section as seen in Figure 1. The innermost layer of cementum, which exhibited radial structures in the optical microscope, is more radiolucent than the peripheral regions. Titanium target. ×160.

Figure 3 Silver-shadowed replica of the ground section adjacent to that illustrated in Figure 1. The surface of the ground section was etched for 20 seconds in 0.1 N HCl prior to replication. The radial orientation of the embedded periodontal fibers in all layers of the cementum can now be demonstrated. ×160.

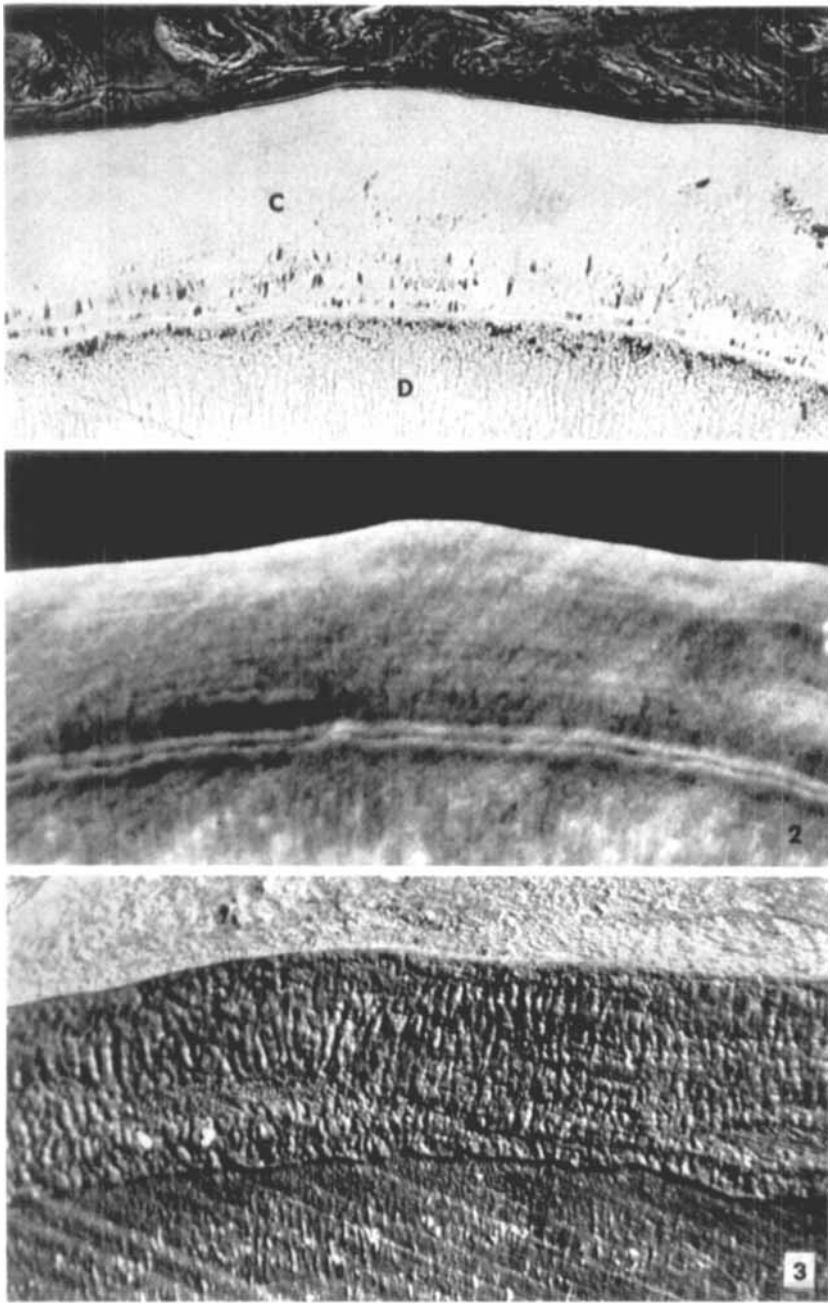
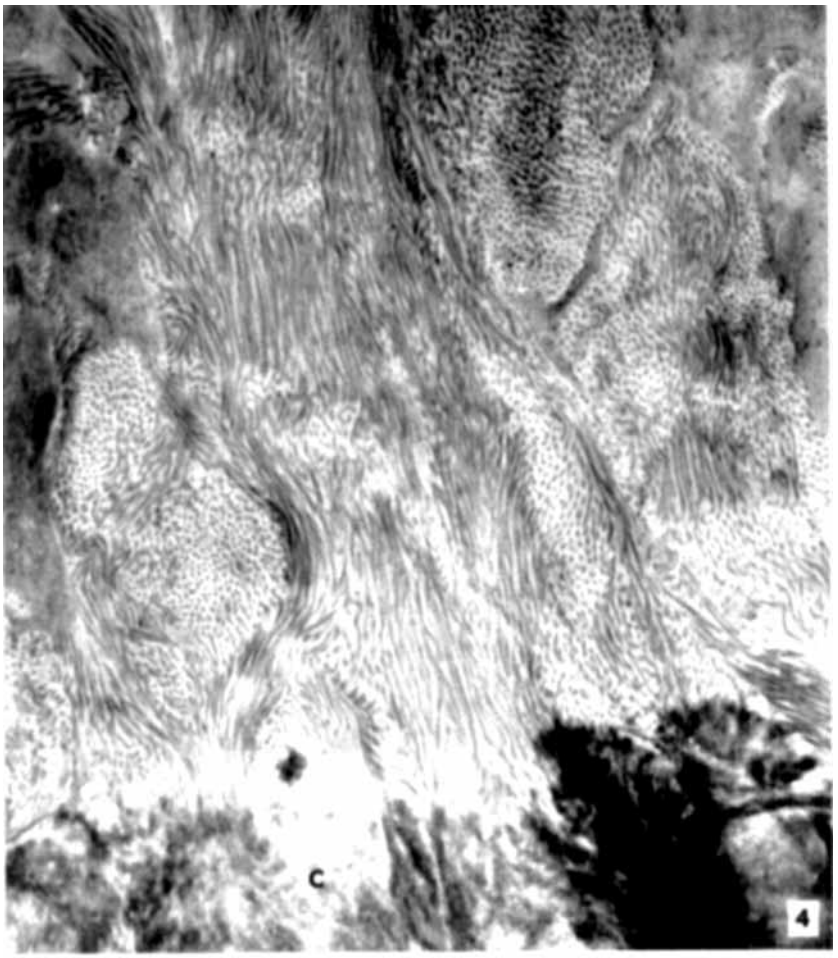

C
D
1
2
3

Figure 4 Electron micrograph of the surface of acellular cementum. Bundles of densely packed collagen fibrils are inserted into the cementum (C) more or less at right angles to its surface. ×10,000.

Figure 5 Cementum surface at higher magnification. The calcifying surface is characterized by small pyramids of calcified material which protrude from the cementum along the inserted collagen fibrils. Each projection corresponds to one fibril. ×40,000.


C
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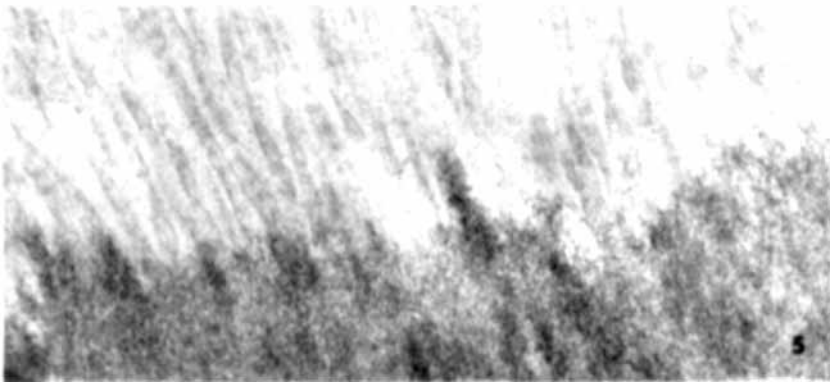
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Figure 6 Another region of acellular cementum formation. The surface is more irregular than in Figures 4 and 5. Calcification has started within a bundle of fibrils which are oriented parallel to the cementum surface. ×14,000.

Figure 7 The cementoblasts are located at a distance of 3 to 5 microns or more from the calcification front of the acellular cementum. CM-cell membrane, N-nucleus. ×14,000.

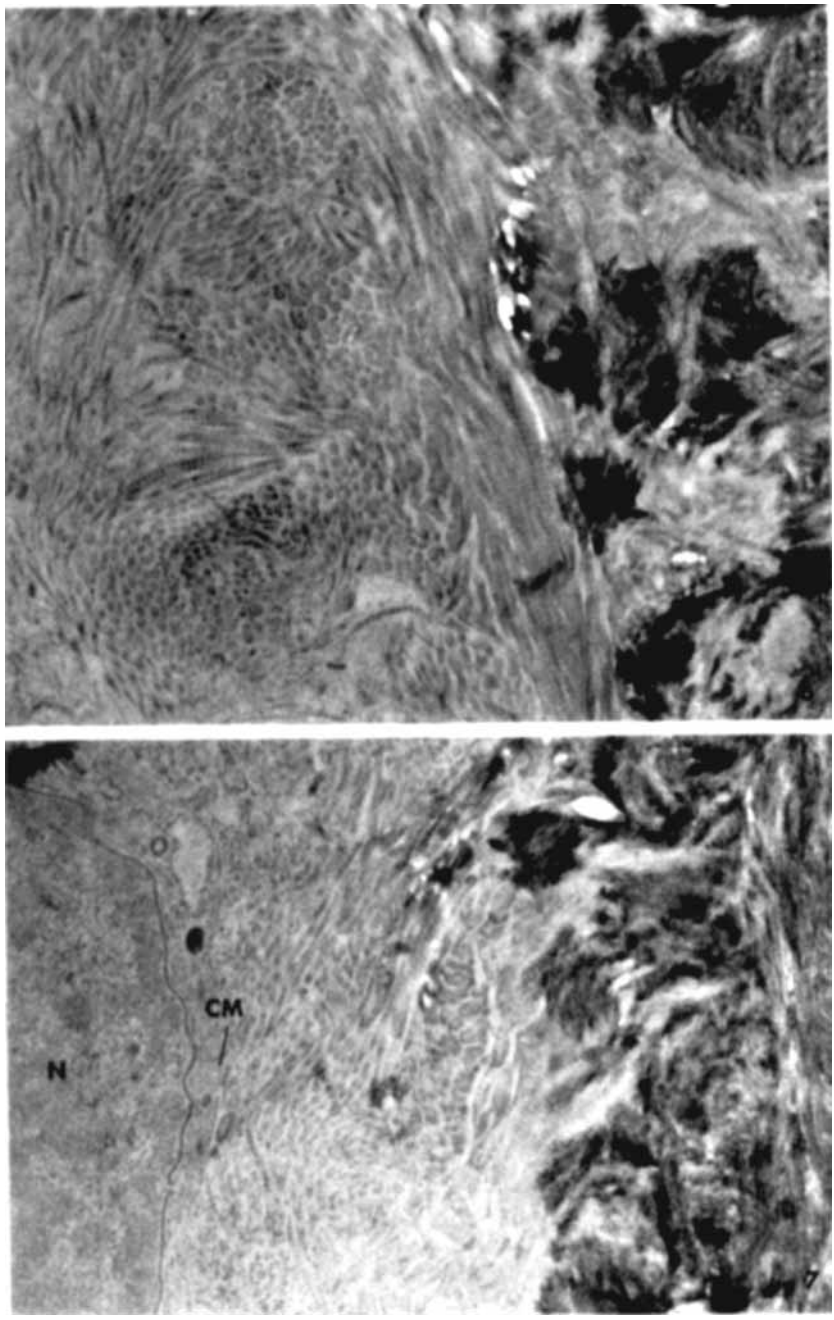

CM
N

Figure 8 Typical appearance of acellular cementum. The matrix contains wide sheets of parallel collagen fibrils, and the mineral crystals have been deposited parallel to these fibrils. Arrow indicates direction toward cementum surface. × 6,000.

Figure 9 Electron micrograph of the innermost layer of acellular cementum. This zone contains partly calcified or uncalcified fibrous structures which extend from the region of the cemento-dentinal junction (CDJ) in radial direction for a length of 20 to 30 microns. C-cementum, D-dentin. × 2,000.

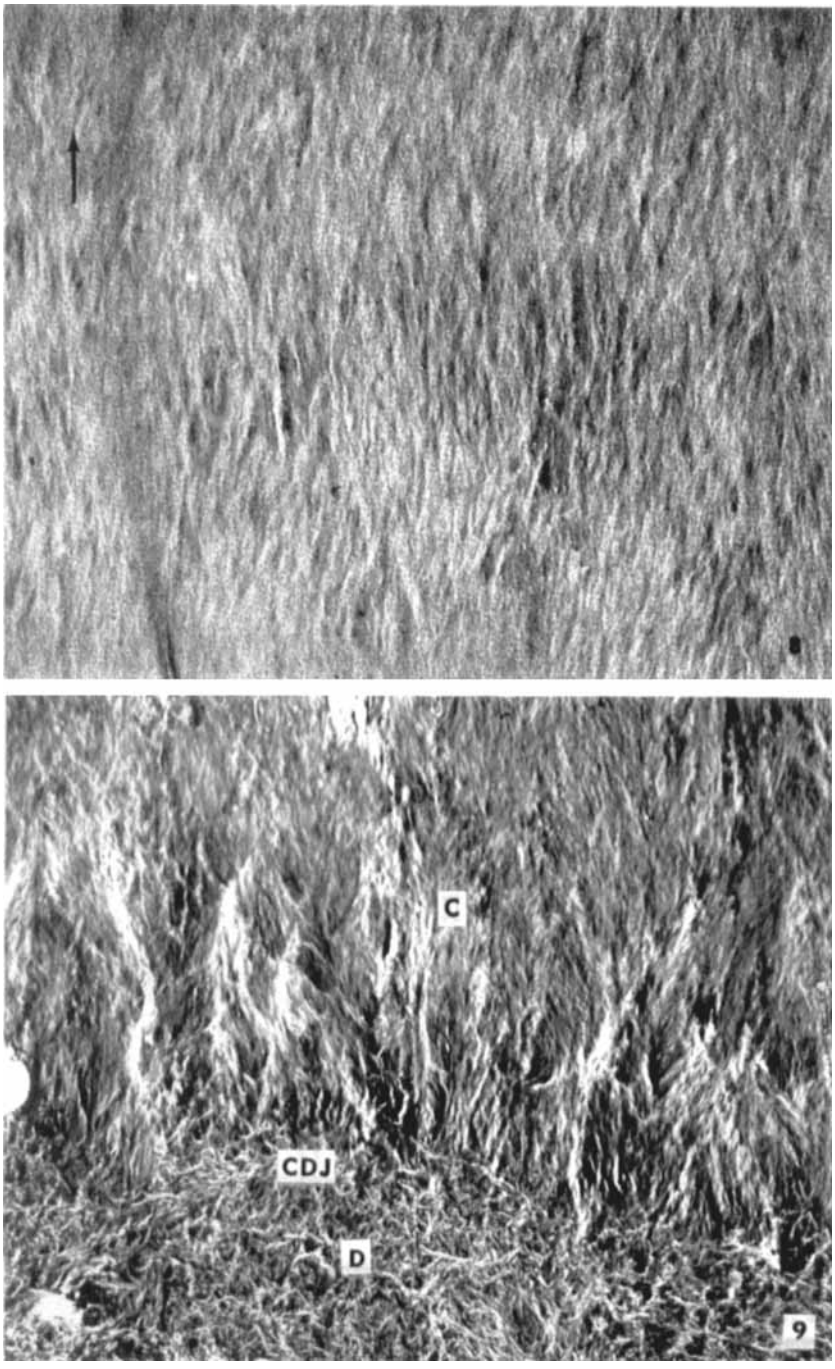
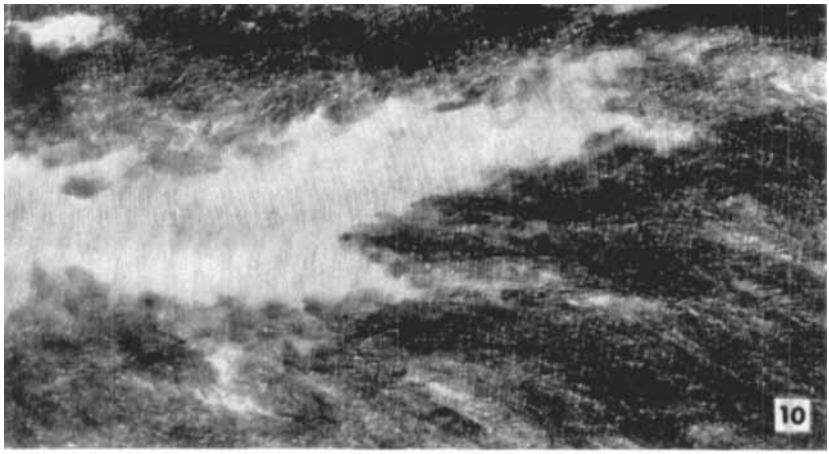

C
CDJ
D
9

Figure 10 Higher magnification of an area similar to that in Figure 9. The presence of matrix fibrils in the uncalcified space is evidenced by the typical collagen cross banding. The uncalcified space is lined by platelike mineral crystals which are considerably larger than those found at the calcification front (compare with Figure 5). ×50,000.

Figure 11 Cellular cementum. Concentric incremental lines and radially oriented Sharpey's fibers can be seen near the surface as well as in deeper layers of the tissue. C-cementum, D-dentin. Transmitted light. 45-micron thick ground section from the apical region of an upper first bicuspid. ×160.

Figure 12 Microradiograph of the same section as seen in Figure 11. Radially oriented, radiolucent lines which indicate the presence of uncalcified or partly calcified Sharpey's fibers can be seen in all layers of the cementum. Titanium target. ×160.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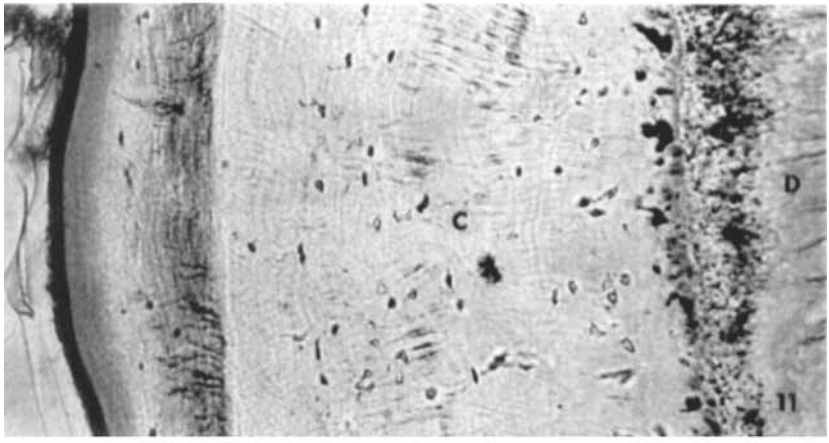
C
D
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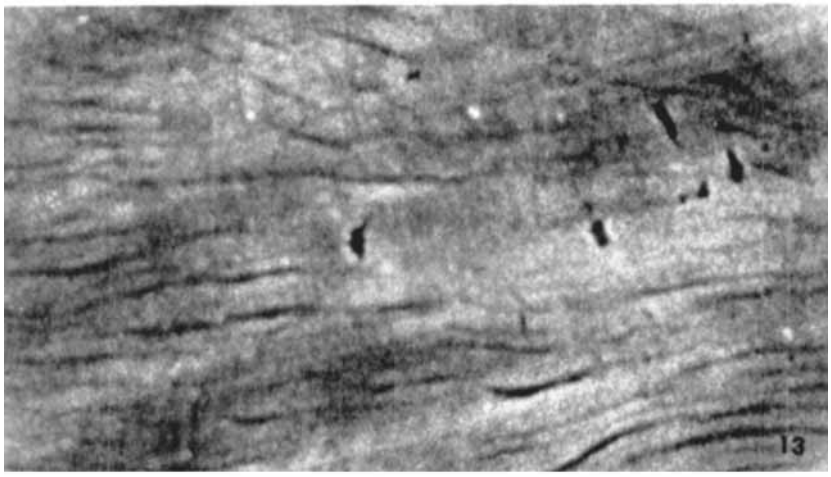
12

Figure 13 Microradiograph of the same section as illustrated in Figures 11 and 12, after the section has been ground to a thickness of about 10 microns. The width of the individual uncalcified channels (up to 5 microns) and the distance between them (10 microns or more) can now be evaluated. Some of the fibers can be followed for a considerable distance (100 microns or more) through the calcified tissue. Aluminium target. ×400.

Figure 14 Electron micrograph of the surface of cellular cementum. The cementum matrix contains irregularly arranged bundles of fibrils. Calcification foci are present in the precementum within a 5-micron wide zone at the surface of the continuous part of the cementum. ×10,000.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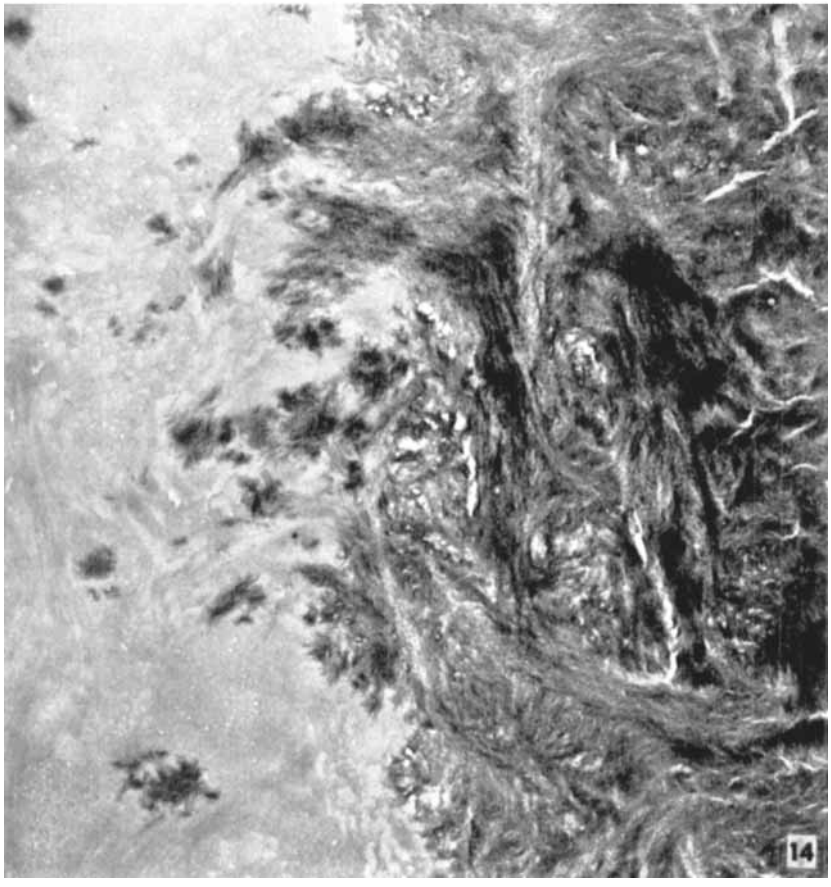
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Figure 15 Tangential section through cellular cementum. Several cross-sectioned Sharpey's fibers can be identified. These fibers are separated from each other by more irregularly arranged fibers. Each Sharpey's fiber is more or less circular in cross section and consists of an irregularly shaped, uncalcified core, surrounded by an electron-dense peripheral part. The fibers in this section are 10 microns or less in diameter, and the distances between the centers of adjacent fibers are 10 to 25 microns. Specimen obtained from ground section adjacent to that illustrated in Figures 11, 12 and 13. ×2,000.

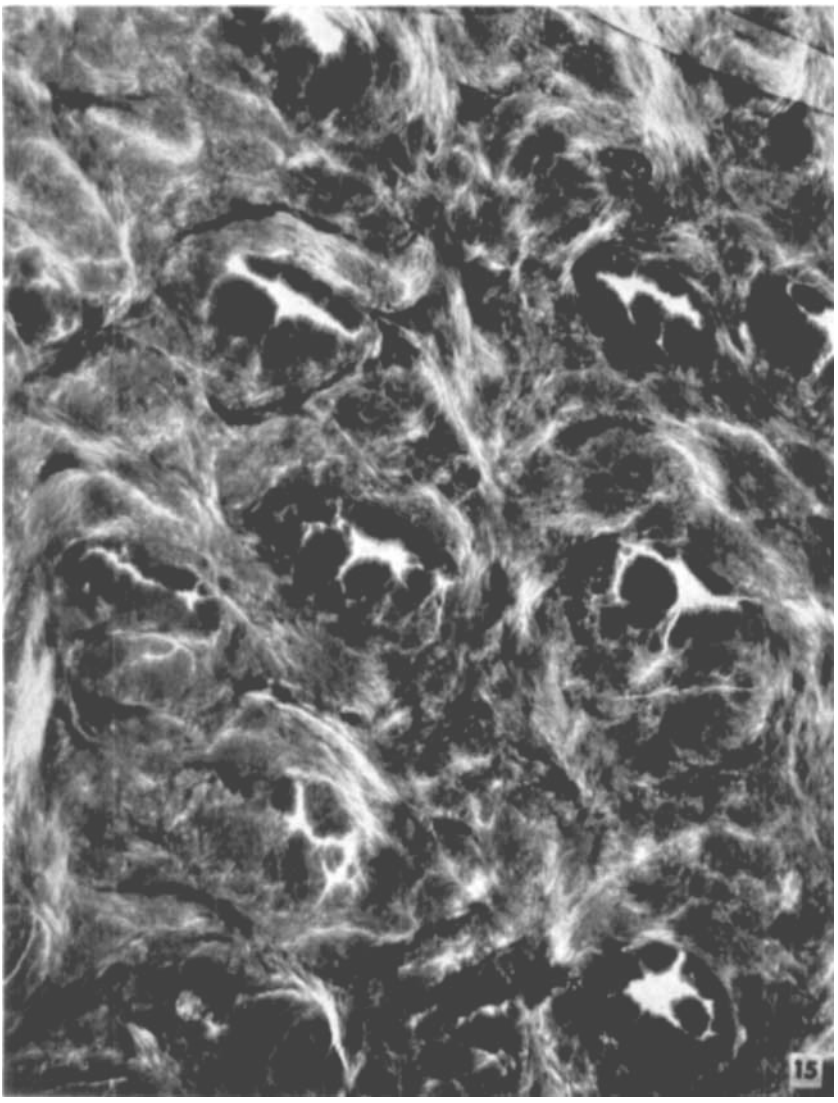
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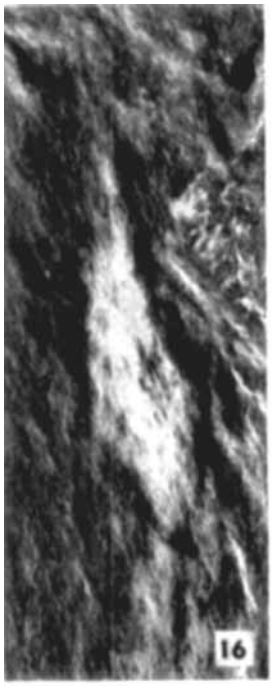
Figure 16 Obliquely sectioned Sharpey's fiber in cellular cementum. The uncalcified core contains typically cross-banded collagen fibrils and is bordered by platelike mineral crystals. × 20,000.

Figure 17 Decalcified cross section of a Sharpey's fiber in cellular cementum. Cross-sectioned collagen fibrils are located within the core, as well as within the peripheral portions of the fiber. The core of the fiber has taken up more phosphotungstic acid stain during the decalcification than the surrounding part. × 10,000.

Figure 18 Cellular cementum containing fibers (F) which are oriented parallel to the root surface. Each fiber is approximately 10 microns in width and homogeneously calcified. × 2,000.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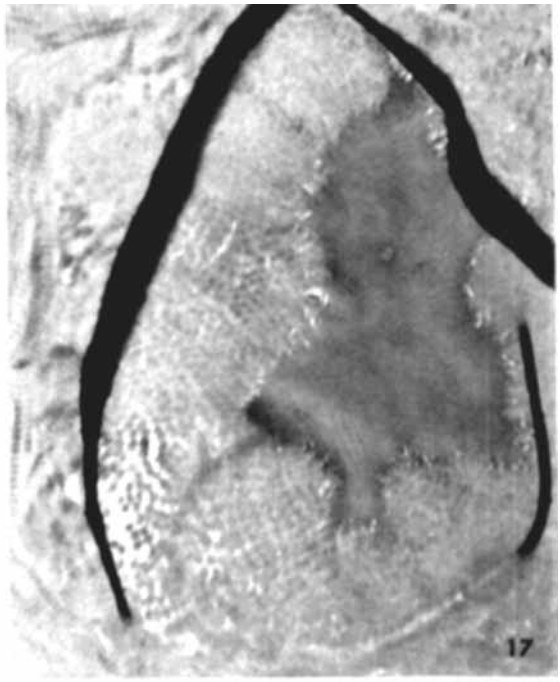
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F
F
F
18

Figure 19 The hydroxyapatite crystals at the surface of cementum appear as flat plates of low electron opacity when they are oriented in the plane of the section (arrows), and as thin, electron-dense profiles when they are seen on edge. Acellular cementum. × 100,000.

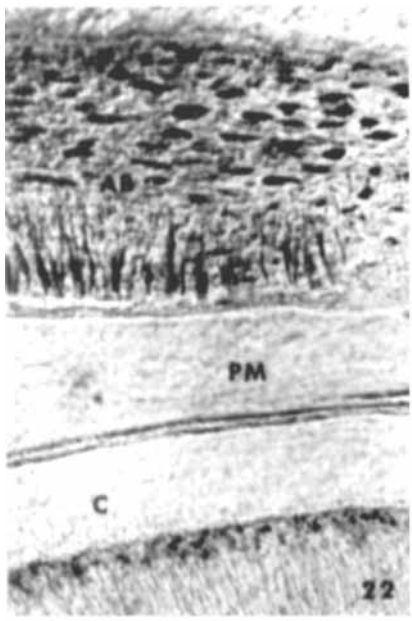
Figure 20 Crystals in deep layer of cementum. Great variations in length and width among the flat crystals of low electron density are evident. Their thickness, as revealed by the crystals standing on edge, shows little variation. × 100,000.

Figure 21 Surface layer of acellular cementum. The crystals seem to reach their mature size within 1 to 2 microns from the surface. This specimen has been treated by ethylenediamine to remove the organic components. × 100,000.

Figure 22 Ground section through alveolar bone, periodontal membrane, acellular cementum, and dentin. The Sharpey's fibers appear as dark lines of varying length and width in the alveolar bone (AB), while such fibers are not visible in the acellular cementum (C). PM-periodontal membrane. Cross section through the middle root region of a lower first molar, ×160.

Figure 23 Microradiograph of the ground section illustrated in Figure 22. Radiolucent lines are seen within the alveolar bone in the region which contains embedded periodontal fibers. Copper target, ×160.

Figure 24 Electron micrograph of alveolar bone. Same specimen as in Figures 22 and 23. Two Sharpey's fibers can be followed from the bone surface into the calcified tissue. OC-osteocyte, PM-periodontal membrane, ×4,000.



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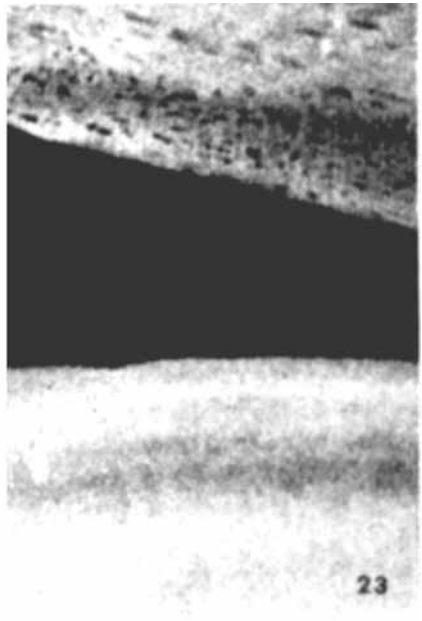

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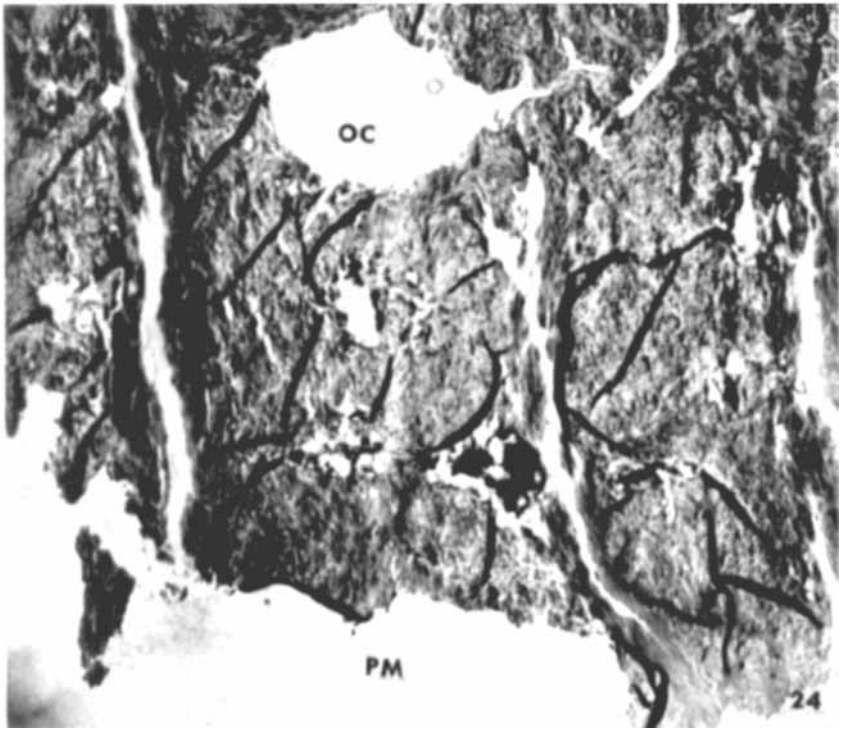

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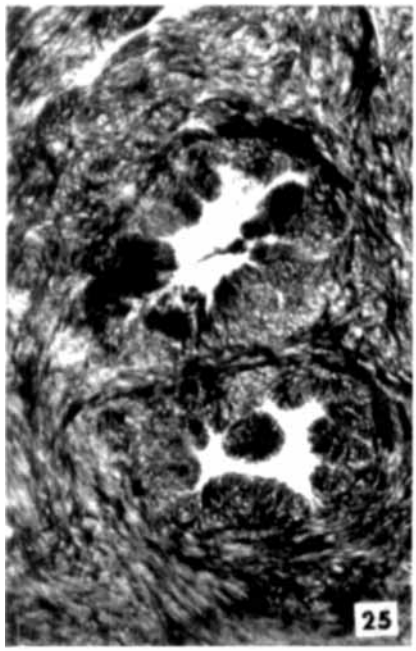
Figure 25 Tangential section through alveolar bone. Like those of cellular cementum, the Sharpey's fibers in alveolar bone consist of an uncalcified core surrounded by a highly calcified peripheral portion. ×4,500.

Figure 26 Cross section of an exceptionally wide and well calcified Sharpey's fiber in bone. The diameter of this fiber is 20 microns. ×2,700.

Figure 27 Selected area electron diffraction pattern from a longitudinally sectioned Sharpey's fiber (the fiber seen near the left edge in Figure 24). The arcing of the 002 and 004 reflections indicate that the crystals are preferentially oriented.

Figure 28 Selected area electron diffraction pattern obtained from the calcified portion of a cross-sectioned Sharpey's fiber. The absence of the *ool* reflections indicate that the crystals in this region are oriented parallel to the electron beam. The 211, 112 and 300 reflections, as well as other reflections, form complete circles, indicating a random dispersion of the crystals about their c axes.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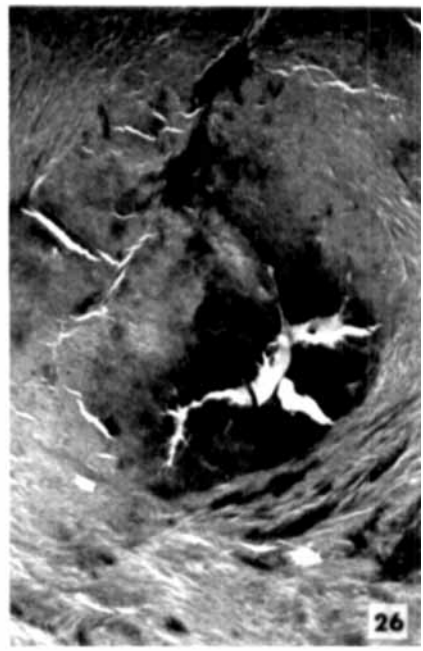
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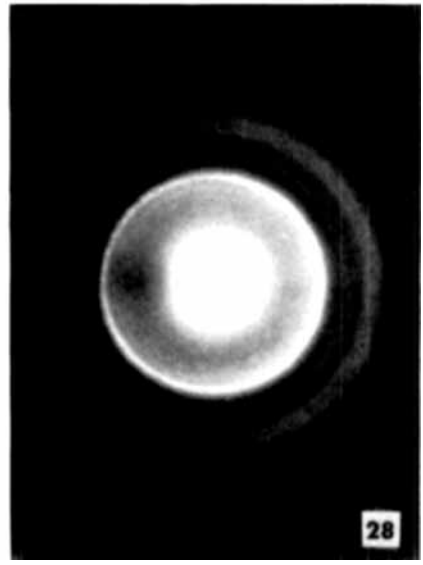
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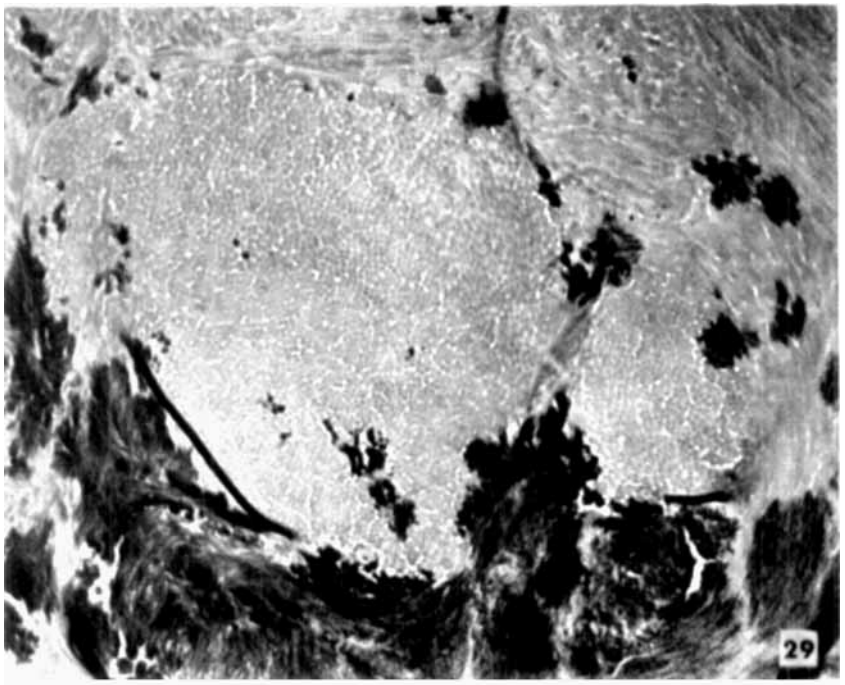
Figure 29 Near-tangential section through the surface of alveolar bone. Two cross-sectioned periodontal fibers entwined by thin bundles of fibrils can be identified. More calcification foci are located within the latter group than within the periodontal fibers. ×5,000.

Figure 30 Canaliculi in alveolar bone. These uncalcified channels contain cytoplasmic extensions of the osteocytes. The course of the collagen fibrils in the immediate neighborhood is independent of the orientation of the canaliculi. ×12,000.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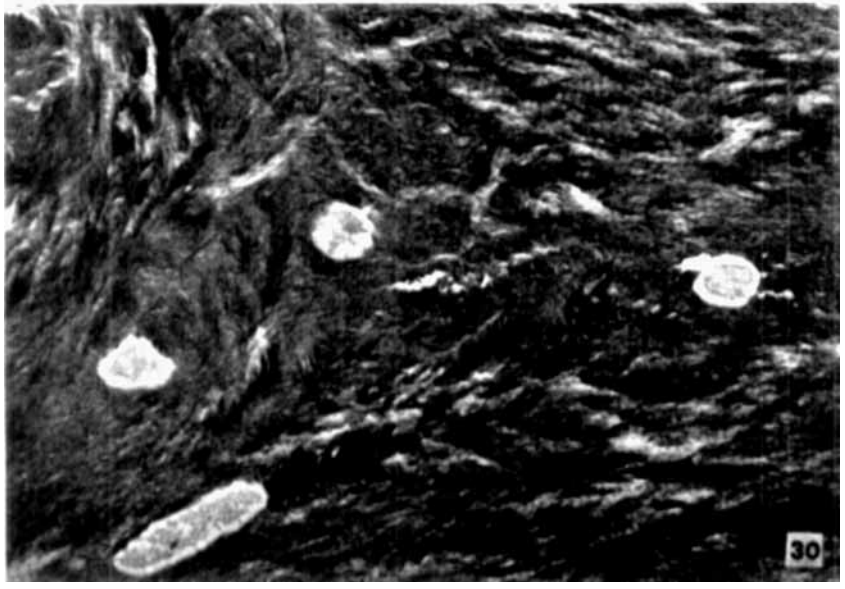
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