HISTOLOGIC RESPONSE OF HUMAN PERIODONTAL LIGAMENT TO TOOTH MOVEMENT FORCES SUBSEQUENT TO INITIAL TOOTH MOVEMENT REACTION

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INTRODUCTION

The biological mechanisms of tooth movement have been studied extensively over the years. The earliest investigative approach was experimentation on various laboratory animals. Most of those studies led to a description of the pressure-tension theory of tooth movement, whereby resorption occurs on the alveolar pressure side and bony apposition on the alveolar tension side of the tooth being moved. Reitan(1), who has been responsible for the majority of human studies in this area, has corroborated this pressure-tension theory using orthodontic subjects.

Two other related phenomena documented in human studies are the "cell-free" zone and undermining resorption. First described by Sandstedt(2), the process of undermining resorption occurs in marrow spaces of alveolar bone adjacent to pressure areas when the resulting periodontal ligament compression occludes blood vascular channels and destroys vitality of the PDL in these areas. A "cell-free" zone is thus created which precludes any frontal resorption of alveolar bone on the pressure side. Osteoclasts in neighboring marrow spaces gradually resorb the bone subjacent to the compressed PDL area until the "cell-free" zone has been eliminated and vitality restored.

These histologic findings have been utilized to help explain the clinical observation of a lag phase during tooth movement. Using the technique of Reitan, Buck[3,4] and others have examined the order and timing of histologic events during tooth movement. But one of the questions left unanswered as yet is whether or not a new "cell-free" zone and resulting lag phase occur every time a force is reapplied to a tooth.

The purpose of this study was to determine if the tooth movement continues unchecked as a frontal resorptive process once the initial movement begins, or rather if the undermining resorption sequence of events recur after a period of rest and repair. Also if, indeed, evidence points to the latter case, does the rest and repair period affect future tooth movement?

It is hoped that the elucidation of the histologic picture after reapplication of tooth movement forces may definitely have some bearing on clinical treatment timing. Therefore, it was felt essential to examine this clinically important problem in human subjects.

LITERATURE REVIEW

From the earliest days of orthodontic treatment, it has been axiomatic that a force placed on a tooth can produce movement of that tooth. However, the exact biologic mechanism for this phenomenon, although the subject of much study and hypothesis, has not yet been fully delineated. Various theories have been proposed to explain this process[5,6,7,8], but the oldest and most widely accepted is the pressure-tension theory of tooth movement.

The evolution of this theory began in the late 1800's, but Sandstedt[2] in 1904 first published information describing it as a histologic process. His experimental method involved tipping the maxillary canines of a dog lingually by means of jack-screws on a labial arch. Upon histologic examination, he noted bone resorption on the pressure side and bone deposition on the tension side. He also used the term "undermining resorption" to describe the process of removal of necrotic PDL tissue caused by the compression of the "peridental membrane" by heavy pressure. He noted that this material had to be removed by resorption from alveolar marrow spaces before tooth movement could begin again.

A few years later Oppenheim[9] conducted a tooth movement study on deciduous teeth of baboons that revealed pressure side alveolar bone resorption and tension side bone deposition along stretched tissue bundles in the direction of pull. Many other investigators have performed animal tooth movement studies, such as Johnson, Appleton and Rittershofer[10], Schwarz[11], Marshall[12], and Macapanpan[13]. The majority of these studies corroborated the pressure-tension theory.

Herzberg[14], Hemley[15], and Stuteville[16] were among the earliest of investigators in human orthodontic tooth movement material, with Herzberg being the first in this country to report on a human tooth movement study. He utilized an orthodontically-tipped maxillary bicuspid of a single patient as his material; his findings were similar histologically to those of his predecessors who had experimented with animal tooth movement. Information from these and other early tooth movement studies formed the foundation of our understanding of the histologic process of tooth movement, but Reitan[17-23] is the individual responsible for the great bulk of human studies from 1951 to the present. In recent years, Atherton[24] and Edwards[25] have engaged in human tooth movement, but have reported exclusively on the gingival response to such movement.

The best description of the histologic process involved in pressure-tension tooth movement has come from Reitan's prolific work. His investigative method involved applying a force to maxillary premolar teeth, which were subsequently removed surgically along with a small segment of attached alveolar bone. In his earlier studies[17,18], Reitan reported that the cell-free PDL area on the pressure side of a tooth being moved varies in size and frequency in relation to the type of force used (i.e., intermittent vs. continuous) and the magnitude of the force. He noted that lighter and intermitten forces tended to create fewer and smaller areas of cell-free PDL.

In studies a few years later[1920], Reitan discussed the histologic reason for the observable "lag time" at the start of any tooth movement procedure. He stated that the compressed cell-free area of the PDL brings a tooth to a standstill for a certain period of time, until the entire cell-free area has been undermined by osteoclastic resorption in the alveolar bone marrow spaces; then the tooth will suddenly move. According to Reitan, several variables are involved in the formation of cell-free areas and concomitant lag phase. First, intermittent forces create cell-free areas less extensive in size and shorter in duration than those caused by continuous forces, because the compression is relieved for a period of time every day allowing revitalization of the PDL. Second, the cell-free PDL is seen more frequently during the initial stage than later stages because of the density of the inner compact layer of alveolar bone. As soon as the compact bone layer is resorbed, the tendency to form cell-free areas decreases. Third, light forces (less than 125 grams) should be used for most tooth movement because of reduced incidence of cell-free PDL formation and consequent lag time. Reitan maintained that if the pressure is strong during tooth movement, new areas of cell-free PDL will be created as soon as the first one is eliminated.

In his later work[21,22,23], Reitan reiterated many of his previous findings concerning the formation of the cell-free PDL area on the pressure side, and expanded his observations concerning initial tooth movement. He divided the duration of initial tooth movement into two parts called the initial and secondary period. The initial period of movement, lasting two or three weeks, included slight movement due strictly to PDL compression and an extended time segment of no movement, during which undermining resorption eventually breaks through into the cell-free PDL area. The secondary period, found after the cell-free PDL tissue has disappeared following undermining resorption, was considered a period of steady movement allowed by direct bone resorption.

In recent years, studies have been published dealing with a variety of aspects of the pressure zone during initial tooth movement. Kvam[26], in a study of rat molars, used several staining methods supplemented by autoradiographic and micrographic techniques to identify the histologic characteristics of the cell-free zone at various time intervals of 2-9 days after force application. Rygh[27] used electron microscopy to characterize ultrastructural changes in PDL cells on the pressure side of rat molars following tooth movement of 30 minutes to 28 days. The findings in both of these studies were not inconsistent with those of many earlier studies utilizing less sophisticated experimental designs. In a human tooth movement study, Buck and Church[3] attempted to document the order of histologic events occurring in the PDL pressure zone at 7-day intervals for 28 days. At the 7-day interval, findings were narrowed PDL spaces and cell-free areas with undermining resorption. After 14 days, the PDL space had widened and alveolar bone resorption was mostly frontal. Specimens at 21 days showed even wider PDL spaces, no osteoclastic activity, and PDL reorganization commencing. The 28-day group exhibited principally fiber and cell reorganization.

It is evident from the literature cited that the histologic processes involved in initial tooth movement have been well researched, although perhaps not completely elucidated. However, the histologic effect of reapplication of force prior to complete tissue repair is not known. The design of this study is to examine the histologic events during force application subsequent to initial tooth movement.

MATERIALS AND METHODS

In this study, experimental tooth movement was carried out in the maxillary dental arches of six girls and three boys, eleven to seventeen years of age, who required removal of premolars for orthodontic treatment. A lingual appliance stabilized by cemented molar bands was fabricated to exert buccal tipping forces of 70 $\pm$ 7 grams on the maxillary first premolars. The force was delivered via double helix finger springs constructed of .018 inch standard stainless steel orthodontic wire, which were soldered to the lingual appliance. Calibration was done by a dead weight loading device to yield the desired force over a 3-4 mm working range.

Patients were randomly divided into the following three groups:

1) Three patients had maxillary first premolars removed ten days following insertion of the appliance.

2) Two individuals served as in-patient controls. That is, no force was delivered to the first premolar on one side of the dental arch, whereas a sequence of ten days of force followed

by ten days of no force prior to removal was utilized on the contralateral side.

3) Four other patients experienced a thirty-day experimental time period in the following sequence: ten-days force, ten-days rest, then another ten-days of force.

The following table illustrates the number of specimens corresponding to each time period.

Table I

Experimental days	No. of Specimens
0 days	2
10 days force	6
20 days (10 days force, 10 days rest)	2
30 days (10 days force, 10 days rest, 10 days force)	8

At the end of each observation period, maxillary premolars were removed surgically to include alveolar bone in a manner similar to that described by Buck and Church. The tissue was rinsed in running water and placed in neutral buffered 10% formalin solution. Twenty-four hours later the crowns of the teeth were removed by a high-speed, water-cooled dental handpiece and returned to the fixative. Decalcification was accomplished in three days by a 5% nitric acid solution; confirmation of adequate decalcification was done by x-ray. The specimens were now washed for 24 hours in running tap water, followed by 4 hours neutralization in lithium carbonate, and then washed again in running tap water for 4 hours. They were stored overnight in 70% ethanol. Dehydration was performed, followed by routine paraffin embedding. Transverse 7-micron sections were serially mounted, beginning two millimeters apically from the most coronal aspect of the specimens, and stained for histologic examination with hematoxylin and eosin, Wilder's reticulum stain, Verhoeff's stain, Mallory's connective tissue stain, and aldehyde fuchsin stain.

FINDINGS

Control sections were representative of a normal PDL. Many cells, mostly fibroblasts, were evident; no osteoclastic activity was noted. Principal fibers, seen clearly in Mallory-stained sections, were densely packed and very orderly in configuration and orientation. Blood vascular elements were numerous in some sections, and always appeared patent. Alveolar bone was mature-looking lamellar tissue. The average PDL width for control specimens was 79 microns. (Table 2) (Fig. 1,2)

The specimens at the 10-day force level showed a very different histologic picture. Several demonstrated a complete cell-free zone throughout most of the PDL space. These cell-free zones were usually accompanied by subjacent undermining alveolar bone resorption. The remaining sections in this category exhibited only small cell-free areas of PDL, commonly associated with points of extreme PDL compression. These specimens contained examples of undermining and frontal alveolar bone resorption. Some principal fiber bundles were still in evidence, but collagenous bundles seemed more densely packed and disorganized. In several, specimens were noted fibrous, immature bone, which indicated new bone proliferation at the 10-day force level. The mean PDL width of 141 microns in this category was found to be approximately 75% greater than the mean control width. (Fig. 3,4,5)

The 20-day (10 days force, 10 days rest) group specimens appeared generally more cellular than those at the 10-day level. PDL reorganization was an almost universal finding as a result of capillary budding, more distinct and properly oriented fibers, as well as increased cellularity. Proportions of bone type varied with individual specimens, but most exhibited the presence of fibrous, immature bone. Osteoclasts were seen occasionally, but evidence of osteoclastic activity was limited. Whenever seen, active alveolar bone resorption was found in small, isolated areas of frontal resorption. Average PDL width in this group was 133 microns, not significantly different from that of the 10-day category. (Fig. 6)

Thirty-day specimens (10 days force, 10 days rest, 10 days force) were generally characterized by cellular, widened PDL spaces, with reorganization an almost universal finding. Large numbers of fibroblasts were found in most specimens, along with nerve and blood vessel elements and assorted vacuoles. The average PDL width of 263 microns was much greater than that of any other group. Limited areas of PDL compression associated with cell-free areas and undermining resorption were found, but the vast majority of osteoclastic activity was in the form of frontal resorption. In several specimens the resorbing alveolar bone front appeared to extend into previous bone marrow spaces. Another salient feature of this group was root resorption. In previous categories root resorption was a rare finding, but 30-day specimens showed frequent examples of this phenomenon. (Fig. 7,8,9)

DISCUSSION

The histologic findings of the control group were very similar to those of other studies, except for the rather narrow average PDL width of 79 microns, as compared to 110-300 microns average width reported by Sicher[28].

Histologic findings at the 10-day force level were consistent with those of other investigators[3]. It was interesting to note different stages of tooth movement within this particular category, however. Several specimens revealed PDL compression and cell-free zones throughout the entire PDL space, with concomitant undermining resorption. Other specimens exhibited only small cell-free areas corresponding to sparse points of PDL compression at which alveolar bone spicules had not yet been resorbed by osteoclastic activity.

Twenty-day specimens presented a few similarities as well as some notable differences from the 10-day group. No significant change in PDL width was found in comparison to the 10-day category. One explanation might be the apparent lack of osteoclastic activity, which would preclude any alveolar bone resorption. It is important to note, however, that osteoclastic cells were in evidence during this time period. Ten days of rest and repair seemed to allow the start of PDL reorganization; capillaries were now seen again in the PDL space, as well as the reappearance of many new cells, particularly fibroblasts.

The findings of greatest importance to this study were those associated with the 30-day specimens. First, the average PDL width of 263 microns was about 225% greater than the average control width and approximately 100% greater than the average of 20-day specimens. This indicated that alveolar bone resorption had taken place during the final 10-days of force application. Second, the PDL exhibited very few areas of compression with accompanying cell-free areas and undermining resorption; the osteoclastic activity was almost exclusively frontal in nature. Third, root resorption was not found to a significant degree in specimens of any time category except 30 days. In those latter specimens root resorption was very frequently observed, leading one to conclude that more than 10 days of force is necessary to cause root resorption.

The foregoing findings revealed the cell-free zone to be a phenomenon of initial tooth movement only. After 10 days of rest and repair following the original 10-day force period, re-institution of tipping force yielded no cell-free zones; only small, isolated cell-free areas in regions of PDL compression were noted. Undermining resorption was seen so rarely in these 30-day specimens, probably because of the widened PDL space. This condition prohibited extreme compression of cellular elements and occlusion of PDL vascular channels which are associated with cell-free zones and resulting undermining osteoclastic activity from adjacent marrow spaces.

These findings tend to indicate that the clinical "lag time" seen during initial tooth movement, presumably due to the formation of cell-free zones, should not be evident in cases where force application is resumed after an interruption of 10 days or less. However, it remains to be determined in further study how much the time period of rest and repair can be varied without producing different results. Also subject to investigation are the histologic effects of varying strength of tooth movement forces on this force-rest-force sequence.

SUMMARY AND CONCLUSIONS

This study was undertaken to ascertain the histologic mechanism of movement after re-application of a tipping force on teeth that have been subjected to an initial tipping force followed by an intervening period of rest and repair. More specifically, an attempt was made to determine if the tooth movement process of undermining resorption associated with PDL cell-free zones seen in initial tooth movement recurs after a period of rest and repair, or if it continues unchecked as frontal resorptive process.

The material for this study consisted of 9 orthodontic patients requiring extraction of maxillary first premolars as a part of treatment. Tipping forces of 70 $\pm$ 7 grams were applied to the teeth in four different time periods, which included 0 days force (control), 10 days force, 20 days (10 days force, 10 days rest), and 30 days (10 days force, 10 rest, 10 force). At the end of each time period, the teeth were removed surgically to include some intact alveolar bone. Specimens were sectioned and stained for histologic examination. Observation was performed under a light microscope.

The following conclusions were made:

1. The cell-free zone of the PDL, with concomitant undermining alveolar bone resorption appears to be associated only with initial tooth movement.

2. Ten days of rest and repair did not completely eliminate osteoclastic cells. Upon re-application of force, frontal resorption of alveolar bone continued without an apparent "lag phase" or reappearance of cell-free zone.

3. An hiatus of 10 days or less in tooth movement forces should not result in any clinical "lag time" in tooth movement upon resumption of force.

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TABLE 2

Mean Periodontal Ligament Width
of Control and Experimental Specimens

Experimental days	Mean PDL width
0 days	79 microns
10 days force	141 microns
20 days (10 days force, 10 days rest)	133 microns
30 days (10 days force, 10 days rest, 10 days force)	263 microns

Figure 1 Control specimen representative of a normal-looking PDL. Scale equals 50 microns.

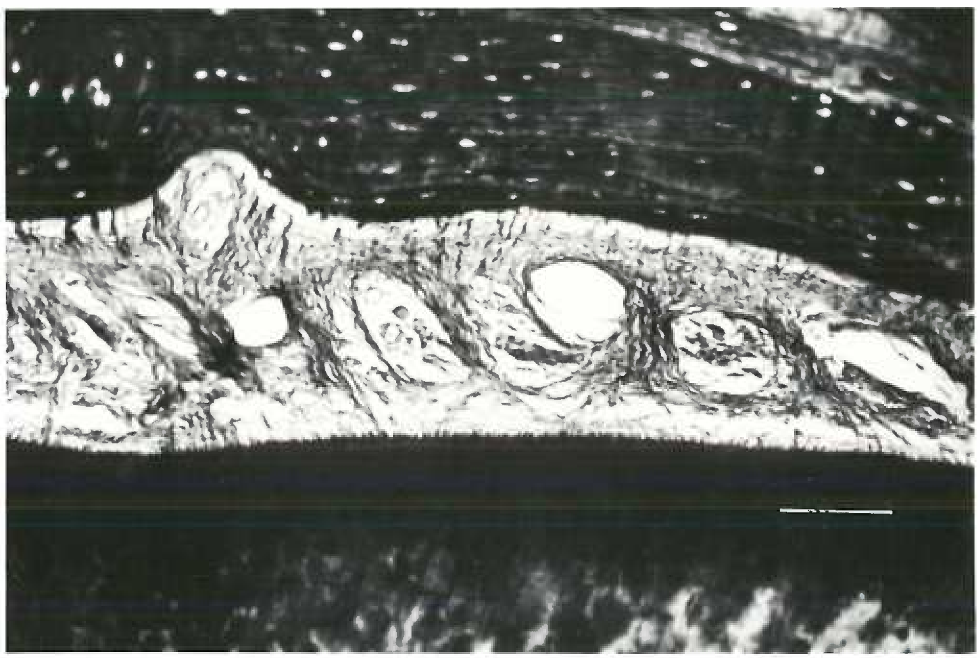

Figure 2 Control specimen with Mallory stain; note principal PDL fibers. Scale equals 100 microns.

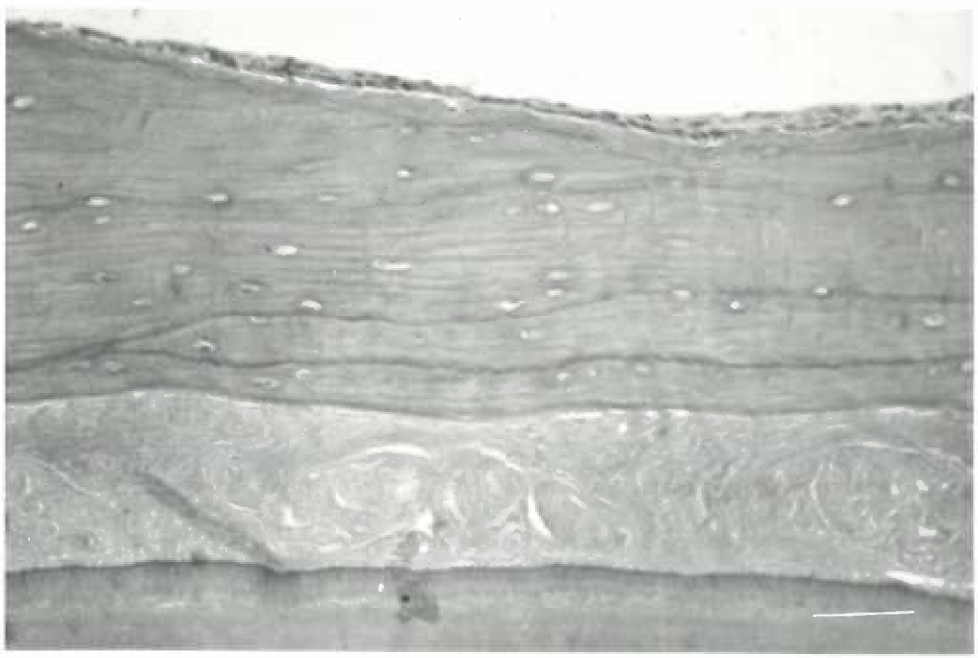

Figure 3 Ten-day specimen showing cell-free zone. Scale equals 100 microns.

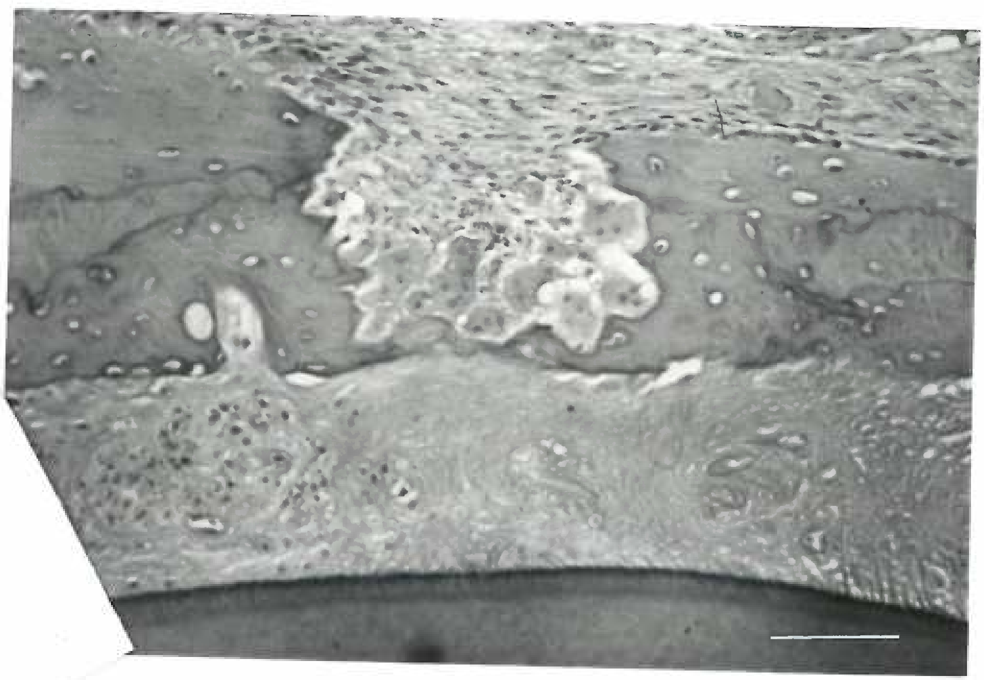

Figure 4 Ten-day specimen showing cell-free area with undermining resorption. Scale equals 100 microns.

Figure 5 Ten-day specimen with evidence of fibrous, immature bone. Scale equals 100 microns.

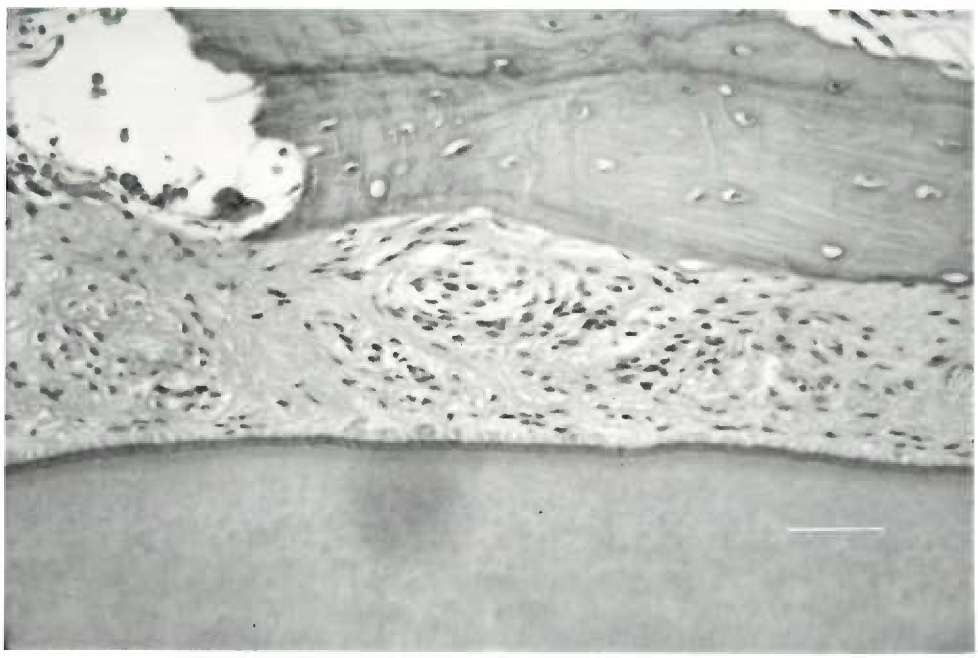

Figure 6 Twenty-day specimen with more cellular-looking PDL. Note osteoclast still in evidence in bone lacuna. Scale equals 50 microns.

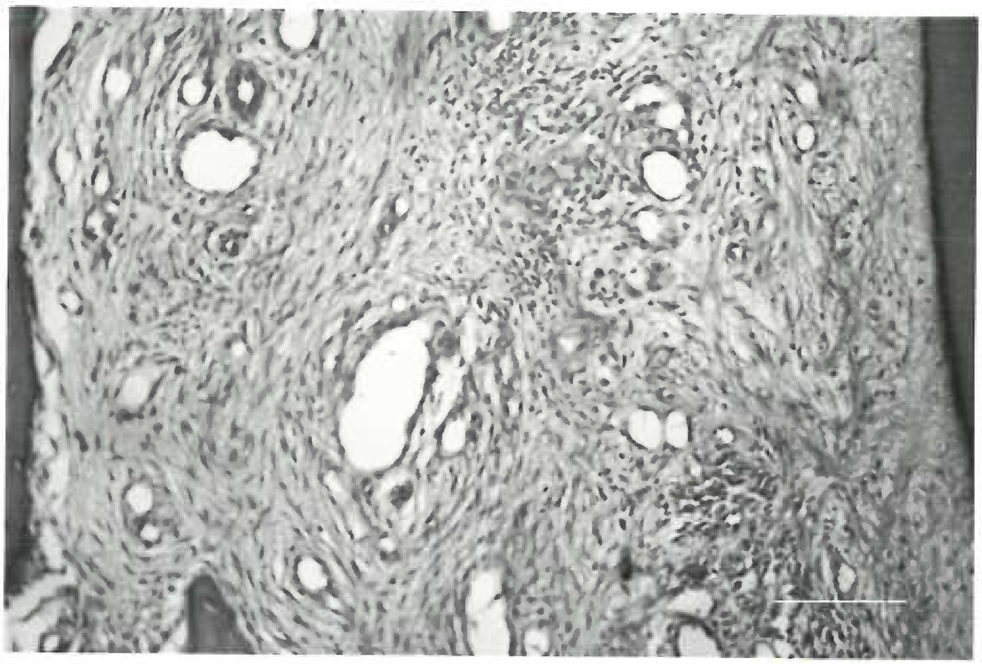

Figure 7 Thirty-day specimen showing PDL reorganization. Scale equals 100 microns.

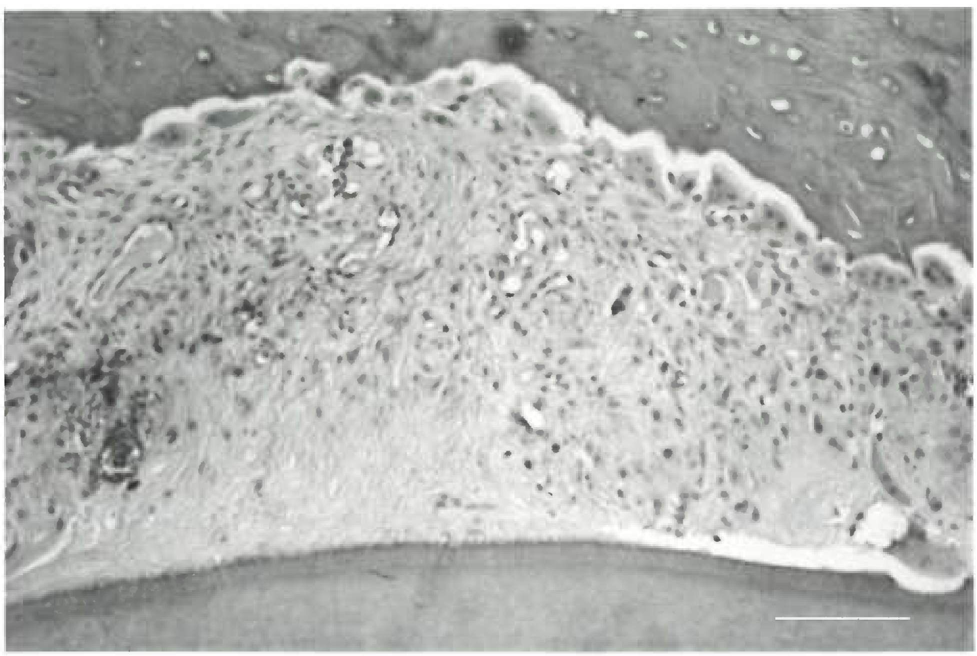

Figure 8 Thirty-day specimen exhibiting frontal resorption. Scale equals 100 microns.

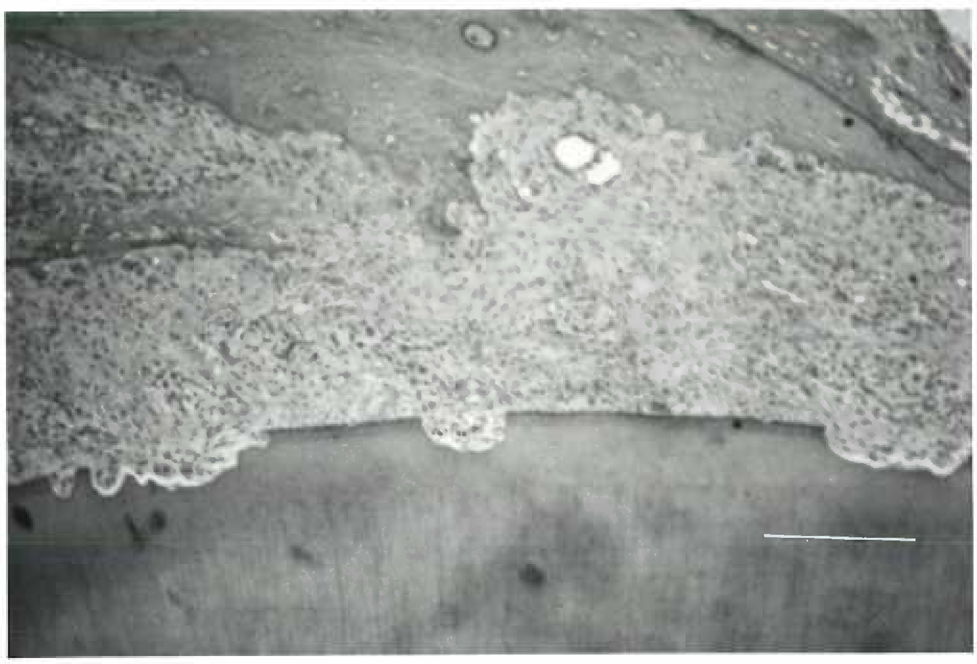

Figure 9 Thirty-day specimen with evidence of root resorption. Scale equals 200 microns.