Comparative Behavior of Human and Animal Tissue During Experimental Tooth Movement

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Information on the tissue behavior during orthodontic tooth movement has been derived from investigations carried out on various species. A review of older and more current literature revealed that a fairly large number of experiments have been performed on animals such as monkeys, dogs and rats, but relatively fewer investigations were based on human material (Table I). Some of the experimental studies on animals belong to the category which may be termed basic biological research, while others have been performed with the aim of obtaining information of value for clinical orthodontics.

It seems relevant to consider whether findings in human and animal structures are comparable and to what extent conclusions can be drawn from observations made in animal experiments. The present preliminary report comprises a comparison and a discussion of some of the findings which are characteristic of experiments performed in animal and human structures.

The material available for observation is based on a large number of experiments performed in man, the dog and the rat; in addition, limited experimental series conducted in the monkey are included. Initially a short description will be given of some of the anatomical and histological details which were observed in the tissues around the nondisplaced control teeth. These observations deal with the character and thickness of the bone, the arrangement of fibrous structures as well as the number of cellular elements.

TABLE I

PUBLICATIONS ON TOOTH MOVEMENT
APPROXIMATE NUMBERS

Some of the experimental series listed have been reported in additional publications. These are not included in the table.

Species	Experiments before 1960	Experiments after 1960
Man	12	6
Monkey	5	4
Dog	10	9
Rat	7	13

THE CONTROL MATERIAL

It is well known that the alveolar bone of young humans usually contains large marrow spaces, open clefts and canals.[56] In young individuals the transitory bone, deposited as a result of tooth eruption, will be remodeled during the subsequent posteruptive period.[27, 55]

In the monkey, large interproximal and interradicular marrow spaces exist, while the alveolar bone plates contain fewer and relatively small marrow spaces.[17] The labial and lingual bone plates in the dog are usually dense and thick (Fig. 1) with well-developed osteones, anatomical characteristics which may be observed in animals as young as eight to nine months.[52]

It may be stated that the alveolar bone of animals is generally denser than the corresponding human structures. This also applies to the circumferential

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Fig. 1 Illustrating the thickness and lack of marrow spaces in the labial and lingual bone plates of the dog.

bone lamellae of the rat which, in addition, reveal absence of osteones as seen by polarized light. Primary osteones have been found occasionally after rats have been fed a diet deficient of calcium, but secondary osteones have almost never been observed in this species.[30]

Lack of marrow spaces is another characteristic of the alveolar bone plates of the rat and bone density has also been demonstrated by densitometric examination of ground undecalcified sections.[58] Other investigators such as Neuman et al. have suggested that the calcium content of the rat bone may be ascribed to its relatively low content of acid mucopolysaccharides.[46]

To some extent differences also exist in the arrangement of the periodontal fibers and the preosseous substances of the supporting structures. Thus, Sharpey's fibers anchored in bundle bone are found in all the four species mentioned above, but the osteoid tissue along the alveolar bone surface is generally less abundant in the rat. In an examination of other bone areas in the rat, Jowsey observed that the uncalcified osteoid layers were rather thin and uneven,[30] an anatomical detail which may be related to the fact that the calcium balance of the rat is controlled by intestinal absorption and less by the bone tissue.[59]

As in other mammals, tissue characteristics denoting a high remodeling activity are observed in the alveolar structures of the rat. Resting and reversal lines as well as resorbed areas are regularly observed along the alveolar bone surface, findings which may be related to a certain periodicity in the bone remodeling processes.[60,68] By comparison, it appears that the preosseous layer along the alveolar bone surface of the dog is appreciably wide and of a regular thickness. To some extent this applies to the bone areas of the monkey as well as to young human alveolar structures.[52,55]

Examination of the supra-alveolar fibers (Table I) reveals certain differences as to thickness and distribution of the marginal tissues of upper first molars. A schematic drawing indicates the main features of the marginal and supra-alveolar fibers (Fig. 2).

There are also structural similarities in the periodontal tissue of these species. This applies to the absence of elastic fibers in the periodontal ligament. In the rat no elastic fibers were seen in the periodontal space while a moderate number was found in the supra-alveolar tissue, a finding corresponding to that observed in human structures.[19,52]

The prevalence of epithelial remnants and their appearance vary in the species mentioned in Table I. While in young human structures strands of epithelial

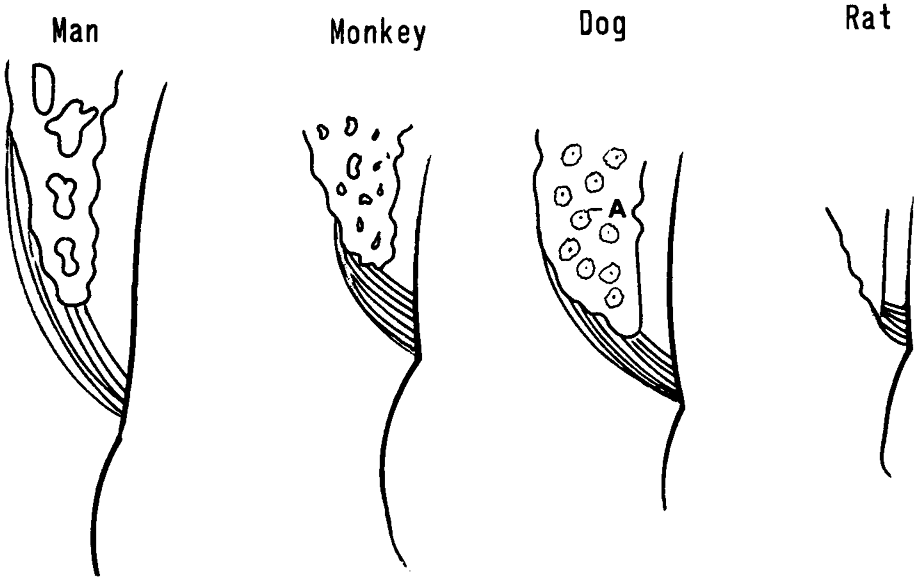

Fig. 2 The marginal and supra-alveolar fibers are conspicuous in the monkey and the dog, less well developed in the rat. In man the supra-alveolar fibers are readily seen following tipping of the experimental tooth. *A*, distribution of osteones in the alveolar bone of the dog.

cells may be observed, there are mainly round remnants of varying size in the monkey and the dog[54] (Fig. 3). In the rat there are few epithelial remnants, a finding which may be influenced by the fact that this animal is monophyodont.[39,74]

The absence of a secondary dentition

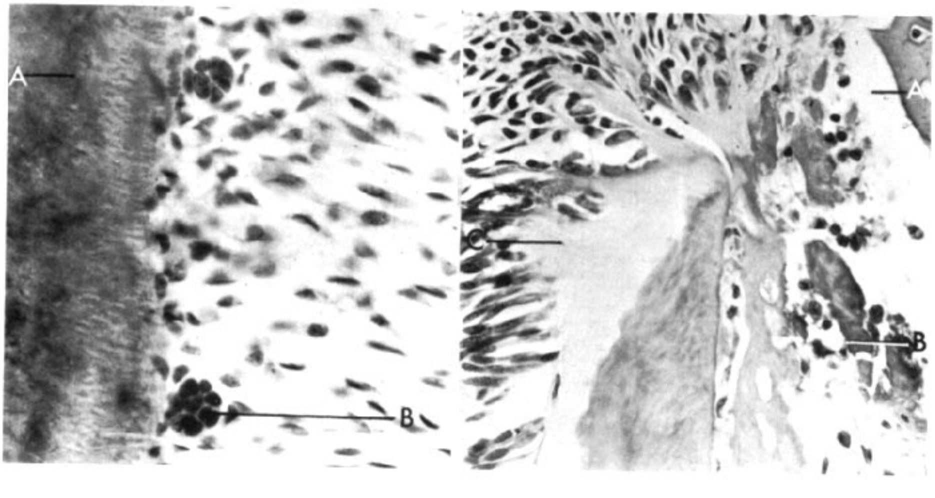

Fig. 3 Left: *A*, root and *B*, epithelial remnant of Malassez in the monkey. Right: Formation of cementum in the rat. *A*, atrophy of the periodontal ligament, area corresponding to *A* in Figure 10. *B*, resorbed and disintegrated apical portion of the root. *C*, thick cementum layer formed as a result of tooth movement, area corresponding to *E* in Figure 9.

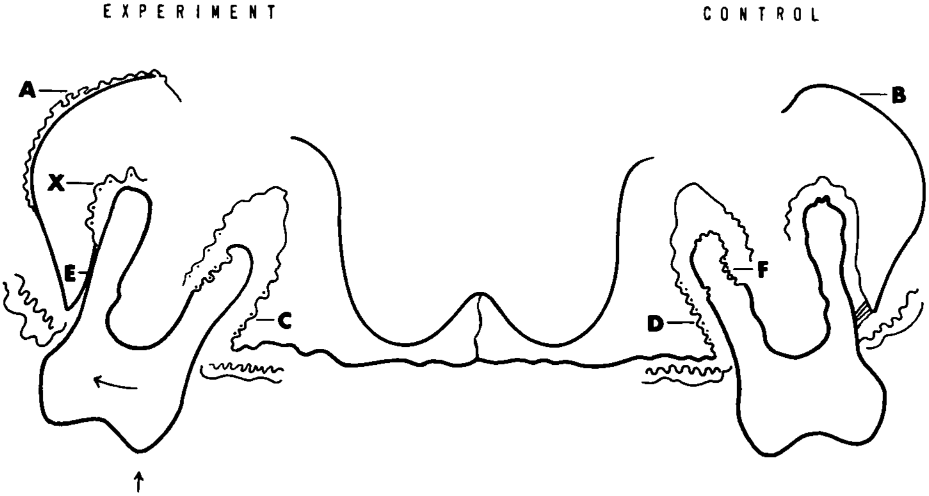

Fig. 4 The experimental tooth and the nondisplaced control tooth in the rat. *A*, maxillary bone deposition as compared with control area at *B*. *C*, persisting bone resorption on the tension side also observed on the control side, *D*. *E*, compressed periodontal ligament, *F*, root resorption as occasionally observed in both the experimental and the control teeth. *X*, pre-existing bone resorption along the apical bone surface.

may possibly also predispose to the prevalence of root resorption observed in rat molars. Such preexisting root resorption was observed more frequently in the marginal than in the apical third of the root. Although resorption lacunae may also be found in the control teeth of some monkeys, these latter findings are rather insignificant as compared with the more or less regular occurrence of root resorption in the rat (Fig. 4).

THE EXPERIMENTAL MATERIAL

The present material comprises teeth with some of the supporting tissues taken from twenty-eight young patients (average age 11.5 years) in which upper premolars had been moved with forces ranging between 20 to 200 gms and for time periods from a few hours up to six weeks.

The animal material consists of two series conducted in seven young monkeys (macaca mulatta) in which upper and lower lateral incisors and canines had been moved with forces ranging between 60 to 200 gms.

In the dog thirty-two teeth with supporting tissues were included. Also these experiments were conducted with forces ranging between 20 to 300 gms. In the rat fifty-four upper first molars were moved in a buccal direction. The forces ranged between 4 gms and 30 gms. Since the experimental results in this animal will be discussed somewhat in detail, a short description of the appliances used will be included.

After banding of the upper central incisors, an .028 sectional arch was soldered to the lingual side of these bands. An .010 spring coiled and welded to the end of the arch provided the active force (Fig. 5). The end of the spring was slightly curved and placed so that pressure was exerted at the lingual surface of the upper first molar. In all cases the corresponding molar of the opposite side was used as control material. Transverse sections were cut so that the experimental tooth and the

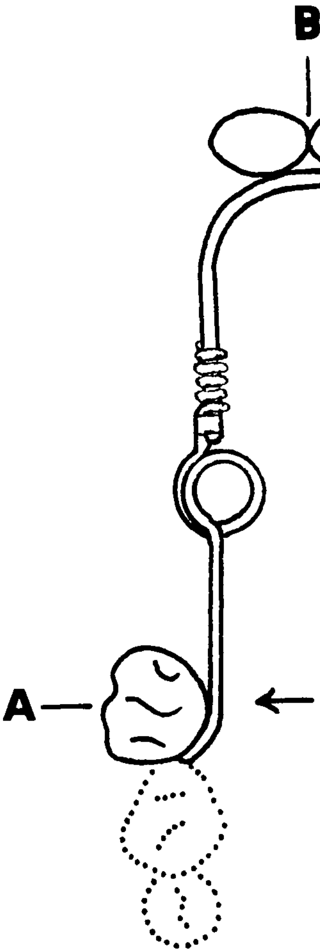

Fig. 5 Schematic drawing of the experimental appliance applied in the rat. *A*, first molar which has five roots. *B*, central incisors provided with bands and sectional arch. Force: 4, 12 and 30 gms. Duration: 2, 3, 4, 7 and 14 days.

control tooth were included in the same section. Serial sections were stained with hematoxylin-eosin. In addition, special staining methods for collagen and elastic fibers were included. In a certain number of cases the cell number was estimated following injections of tritiated thymidine (H_3TDR).

OBSERVATIONS

The majority of the experiments in human and animal structures were per-

Fig. 6 Area representing buccal root of the two middle roots of the first molar in the rat. Lower arrow indicates contact between root and bone surface as a result of atrophy of the periodontal ligament. Frontal bone resorption is seen in adjacent areas. *A*, demarcation line between new and old bone. *B*, a thin layer of compensatory bone. *C*, osteoblasts bordering thick layers of new bone deposited at the "concave" side of the bone wall. Several muscles above line passing to *D*, the end point of bone deposition. Force: 12 gms. Duration: 14 days.

formed as a tipping of the teeth with continuous forces. The results following such experiments are well known. After a certain period of time even a light force causes compression of the periodontal ligament in circumscribed areas located adjacent to the marginal third of the root.[52,55] Initially, very little or no pressure is exerted along the middle and apical thirds of the root (Fig. 6).

In human structures hyalinization of the periodontal ligament is followed by a fairly rapid undermining resorption starting in the marrow spaces or at the alveolar bone wall around the cell free tissue.

In animals hyalinized zones are produced as readily and quite early in a small animal such as the rat.[37,71] Macapanpan, Weinman and Brodie[41] observed hyalinization in the rat after a period as short as six hours and in the present series it was found in all experiments of short duration.

The tissue reaction on the pressure side of the species mentioned in Table I is therefore fairly similar during the initial experimental period. In the monkey and the dog undermining resorption, starting in marrow spaces, is frequently observed, although in cases of high bone density the undermining resorption will mainly be restricted to adjacent areas of the alveolar bone wall.

Another variation is observed on the pressure side in animal experiments. Following application of a strong force for a longer period, atrophic changes may occur on the pressure side, occasionally with elimination of the periodontal ligament. This phenomenon has been observed in the dog in cases of high bone density[56] and also in the rat (Figs. 3 and 6).[37,38]

In humans as well as in the monkey and the dog, tooth movement in a mesial or distal direction is generally followed by a more rapid undermining resorption than observed in a labial or lingual tooth movement.[48] When the tooth is moved in a labial direction against an alveolar bone wall which contains clefts and marrow spaces, undermining resorption is followed by bone formation on the periosteal side. Such compensatory bone deposition is always observed in young human structures, to a varying extent also in adults.[53] Likewise, tipping of the crown portion of the tooth in a lingual direction may elicit bone formation on the periosteal side in an area corresponding to the apical portion of the root. This finding is observed in humans as well as in the monkey and the dog (Fig. 7).

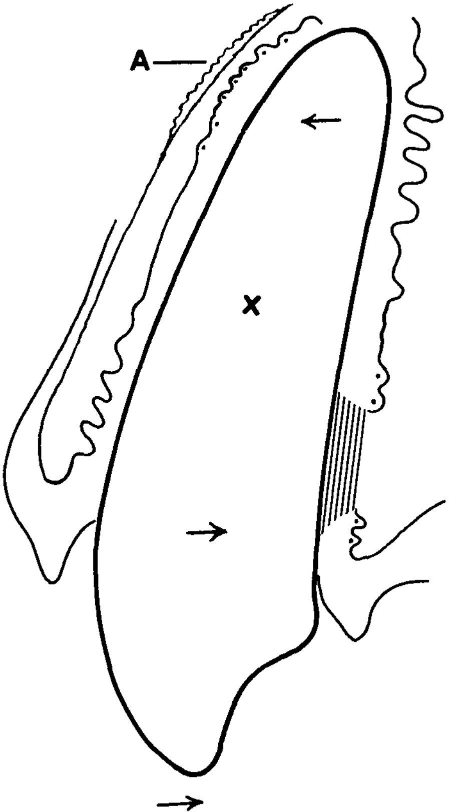

Fig. 7 Illustrating periosteal bone deposition, *A*, following tipping of a second incisor in the dog. Force: 100 gms. Duration: 30 days.

In the rat certain variations exist during the initial stage of tooth movement. Occasionally buccal tipping of first molars resulted in what may be termed undermining resorption on the periosteal side. This type of periosteal bone resorption was observed in eight cases (Fig. 8). In other experiments of longer duration initial periosteal resorption had apparently existed for some time, resorptive changes which gradually had been transformed into periosteal bone deposition.[37] In two instances bone resorption had persisted for a longer period on the periosteal side in an area corresponding to the middle third of the molar roots (Fig. 9). Such periosteal bone resorption is not observed in any of the other species.

Other variations were observed in the rat. In cases in which the experimental tooth was heavily tipped, hyalinization

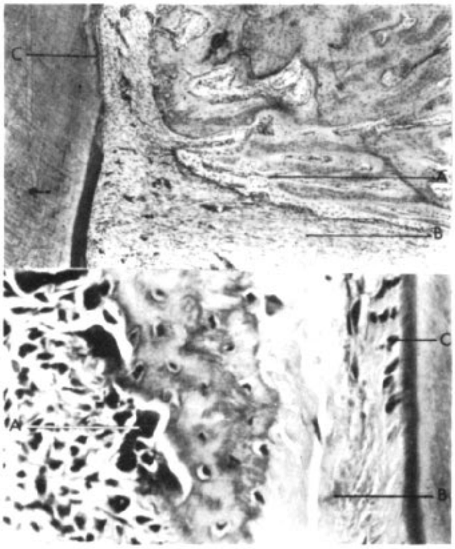

Fig. 8 Above: *A*, new bone layers formed in the monkey as a result of stretching of marginal and supra-alveolar fibers, *B*. *C*, repaired pre-existing root resorption. Below: *A*, periosteal undermining resorption in the rat. *B*, hyalinized periodontal ligament. *C*, remaining cementoblasts. Force: 12 gms. Duration: 6 days.

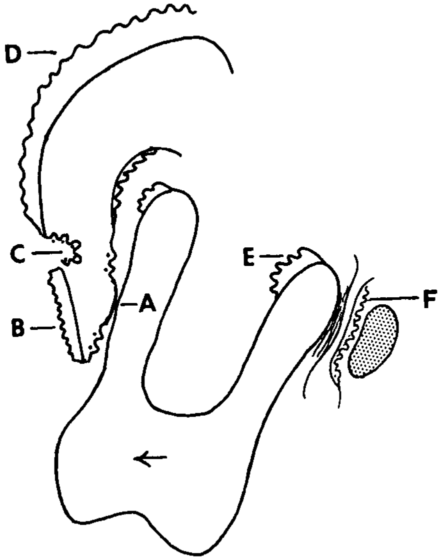

Fig. 9 First molar of the rat, middle roots, following movement of two weeks duration, force 12 gms. *A*, compressed and atrophied periodontal ligament. *B*, bone deposition. *C*, persisting bone resorption observed only in two of 54 animals. *D*, maxillary bone deposition. *E*, deposition of cementoid. *F*, osteophytes formed close to lymphoid tissue.

occurred along the thin bone wall which separates the roots from the lymphoid tissue on the palatal side. In a limited number of cases strong compression of the periodontal ligament had resulted in a rapid formation of osteophytes on the endosteal side of the bone wall (Figs. 9 and 10). Another interesting type of bone deposition was observed in the rat along the curvature of the upper jaw, in other words at a certain distance from the undermining bone resorption (Fig. 4). Such maxillary bone formation occurred in all experiments of 2, 3, 4, 7 and 14 days duration and with forces of 4, 12 and 30 gms.

In many cases root resorption was observed in the rat. Lacunae were present in the control material as well as in the experimental material. These resorption lacunae were located close to or around the cell free zone and were thus partly a result of tooth movement.

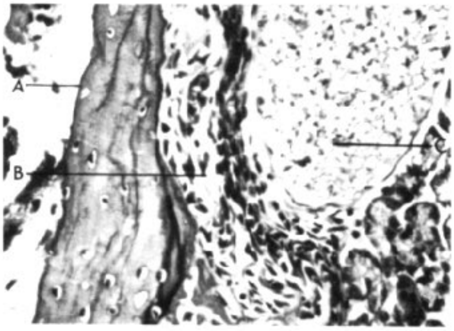

Fig. 10 Area corresponding to *F* in Fig. 9. *A*, bone wall devoid of cells as a result of atrophy of the periodontal ligament. *B*, bone deposition in the form of osteophytes. *C*, lymphoid tissue. Force: 12 gms. Duration: 7 days. In some instances such bone deposition occurred after two days' tooth movement.

Discussion

When evaluating the details observed in an experimental material, it seems natural to consider primarily the influence caused by the metabolism and the anatomical environment, secondly the mechanical factors. Together these factors will determine the result of an experimental tooth movement, but they are closely linked and one can hardly discuss the magnitude and direction of the force without considering the anatomical environment. As an example one may mention the marginal and supra-alveolar structures of the monkey which are well developed (Fig. 8). Tension on these fibers, which are partly anchored in the alveolar bone crest, will soon lead to deposition of new bone layers. Not so in an animal such as the rat in which these fibers are generally less developed, an anatomical environment that may cause a delay in the onset of formative changes. As pointed out by Kindlová and Scheinin[32] the vascular supply of the interdental papilla of the rat is anatomically different from that observed in human structures.

The general influence of the anatomical environment has been discussed in earlier investigations.[52,55] It was shown in these experiments that, provided a chain of osteoblasts and a thin layer of osteoid exist, tension will rapidly increase the thickness of these preexisting structures and deposition of new bone will occur not unfrequently after a period as short as 25-30 hours. If, on the contrary, bone resorption exists on the tension side, formation of new bone will be delayed at least three to four days. In a human control material comprising twenty-three teeth, bone resorption was observed in certain areas on the lingual side in nine cases. Examination of twenty-seven molars in the rat revealed aplasia or bone resorption on the lingual side in twenty-two cases. Not unfrequently the bone surface was lined with a thin dark layer which may consist of sulfated acid mucopolysaccharides.[68] This aplasia and the occurrence of resorbed lacunae on the tension side are likely to cause a delay in the initial bone deposition.[37]

A mechanical detail is the small size of the experimental teeth in the rat, a factor which may lead to a varying localization of the fulcrum in a tipping movement. Following tooth movement in a labial direction it was found that the palatal roots were extruded in some, but not in all cases. Observation of the cell number on the tension side as compared with that of the pressure side, revealed that in several cases no definite variation existed in the rate of formation of new cells. Similar observations were made by Baumrind, following experimental tooth movement in the rat.[8] In the present experiments it appeared that the cementoblasts of the apical third of the roots reacted more quickly to tension than the osteoblasts. Thus the amount and localization of cementoid formed on the apical tension side of the root may indicate the degree of tipping of the tooth (Fig. 3). This rapid deposition is characteristic of cellular cementum in rat molars, a tissue which has been described as osteocementum.[60,61]

Increase in cementoid as a result of tension is also observed in the dog, but initially bone formation is always prevailing on the tension side, notably in young animals. Increase in the thickness of the cementoid layers on the tension side is less marked in the monkey and in human structures.

Tissue changes in the rat

During an initial tooth movement in humans, monkeys, or dogs bone lamellae are laid down on the tension side particularly at the bone surface close to the alveolar crest. In the rat, formation of such osteoid spicules may be delayed. Secondly, while in humans initial hyalinization is observed after a period of thirty to forty hours, in the rat hyalinization may occur after six hours.[41] Thus, cell-free zones of a dura-

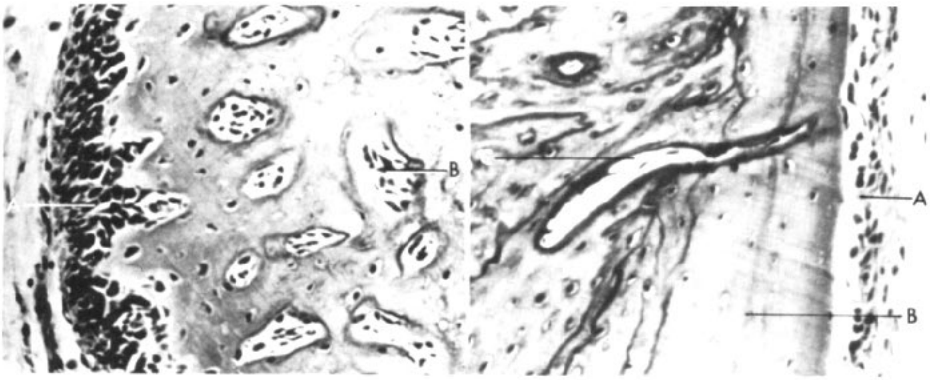

Fig. 11 Left: Area corresponding to *A* in Fig. 4 and *C* in Fig. 6. Note increase in number of osteoblasts at *A*. *B*, marrow space in the new bone. Right: Area corresponding to *B* in Fig. 4. *A*, osteogenic layer with osteoblasts. *B*, dense circumferential bone lamellae. *C*, perforating canal of the bone.

tion of seven to fourteen days were created in all the fifty-four rat experiments of the present series. Other variations exist. In the rat the most conspicuous bone changes occur in the endosteal and periosteal structures. An example may illustrate this observation. Following tipping of a first molar for two days with a force of four gms, hyalinization occurred in the buccal pressure zone (Fig. 4). On the tension side there was a slight increase in the cell number but very little deposition of osteoid (Fig. 6). Only few mitotic cell divisions were observed. In contrast to these findings, cell proliferation and deposition of osteoid occurred along the curvature of the maxilla.

Also after an experimental period as short as two days, similar bone deposition had occurred along the endosteal bone surface corresponding to the apical portion of the mesial root (Fig. 10). The periodontal ligament was partly atrophic. Only small resorption lacunae were seen in surrounding areas on the alveolar side. While the incidence of bone deposition in the latter areas varied considerably, bone formation along the maxillary curvature occurred in all cases. The thickness of these new bone layers was appreciably increased in the experiments of longer duration (Fig. 11).

Among the factors responsible for such maxillary bone deposition one may first consider the hyalinized zones on the pressure side. In the rat force-induced frontal resorption occurred in all cases.[37] This type of undermining resorption is primarily caused by a morphologic bone density and thus also observed in the dog.[56] Frontal resorption and resorption in marrow spaces are both variations of the same biologic phenomenon and closely related to the bone character. The periosteal resorption in the rat is a third variation of the undermining principle (Fig. 8).

While only one case of the whole human material revealed undermining resorption close to the alveolar bone crest, in the rat there was even periosteal bone resorption in as many as eight cases (Fig. 8). The experimental force ranged between four and thirty gms and the duration between two and seven days. Since the osteoclasts in these lacunae gradually disappeared and were followed by formation of osteoblasts and bone deposition, one can not exclude the possibility that periosteal resorption had existed earlier in the experiments of longer duration. It is nevertheless rather unlikely that the thick bone layers formed along the curvature of the maxilla should be a compensatory bone deposition resulting from this periosteal bone resorption. Nor can the bone resorption observed at X in Fig. 4 be related to the maxillary bone deposition.

The latter resorbed lacunae were located adjacent to the apical third of the roots, areas in which the tissues were generally subjected to tension. Examination of twenty-seven experiments conducted for periods of two, four and seven days revealed that resorption along the inner bone surface had persisted in nine cases. Aplastic bone surfaces or incipient bone deposition were observed in this area in other cases, a finding which could be expected since in most instances the apical portions of the five roots were moved away from the bone surface. Bone resorption at the inside of the periodontal space is therefore not likely to be related to this bone formation.

Pressure theories

It is known that a marked hyalinization per se may induce bone formation at the rear side of the alveolar bone. In the rat alteration of occlusal contacts may increase the pressure during tooth movement and thus intensify the compression of the hyalinized tissue. The results of this effect correspond to the observation made by Glickman and Smulow in what they called "buttressing bone formation," i.e., the tendency for compensatory bone layers to be formed rapidly.[26]

Such a reaction is seen in Figure 10 where compression and atrophy of the tissues of the periodontal ligament elicited formation of osteophytes on the endosteal side of the bone wall. Only restricted information is available regarding the histochemical changes leading to such bone deposition. Pritchard ascribed inductive abilities of bone to cellular elements.[51] Lacroix considered the canaliculi as enzymatic pathways in the mechanism of such induction.[40] On the other hand, the bone layers observed at C in Figure 6 can hardly be characterized as a buttressing bone formation.

Another pressure theory should be mentioned in this connection, namely, the bioelectric effect observed at bone surfaces undergoing pressure or deformation.[22] Experiments conducted by Andrew, Bassett, Pawluk and Becker in which they implanted electrodes in the femora of dogs revealed that a weak electric current may lead to an increase in the number of osteoblasts and subsequently bone formation.[4] It has been pointed out also that bending of a bone may lead to bone deposition at the concave surface and that this phenomenon is related to the electronegativity of the area.[6,14,20] In the present experiments this "concave" surface corresponds to areas marked *A* in Figure 4 and *C* in Figure 6. Since maxillary bone deposition was observed after an experimental period as short as two days, one may tentatively suggest that this periosteal bone formation could be the result of a bioelectric effect.[62]

Bone deformation

To what extent bone bending should be considered an important factor during orthodontic treatment was frequently discussed at the end of the 19th century.[21,33] Of the species mentioned in Table I, one must assume that the labial circumferential bone lamellae of the rat were undergoing a certain degree of deformation following tooth movement. Permanent deformation of recently calcified bone spicules in the dog was observed as a result of pressure exerted by the root during relapse of the tooth.[56] Contrary to this finding, experimental tooth movement in a labial direction did not produce any measurable bone deflection (Fig. 1).[52]

In the dog as well as in the monkey the interproximal bone layers are more liable to become temporarily deformed than the labial and lingual bone plates.[56] Similar bending of interproximal bone layers occurs in humans following insertion of a facebow combined with extraoral force. However, as soon as the force is released there is a tendency for the teeth to move toward their original positions.[3] Unless the adjacent bone lamellae consist partly of uncalcified or recently calcified tissue, the pressure will only cause a temporary deformation.

In humans there is occasionally deflection of labial bone plates which have become thin as a result of earlier bone resorption. Measurements of the periodontal space in the control areas may reveal an average width of around 0.25 mm. Following initial treatment with light forces, the width may become appreciably increased as a result of bone resorption. When bringing a tooth, such as a lower incisor, into alignment by adjusting a rectangular arch into bracket engagement, one may disclose that all of a sudden the tooth has been moved over a greater distance than can be explained by the increase in periodontal space width.

Such individual tooth displacement causes a certain deflection of the labial bone wall (Fig. 12).[8,49] At this stage of tooth movement elimination of any new compressed zones occurs rapidly and, as the periodontal space becomes wider following further bone resorption, pressure is no longer exerted. Partly as a result of contraction of displaced fibrous structures, the deformed bone wall tends to move back more or less to its former position. In young persons there is simultaneous formation of compensatory bone layers on the periosteal side (Fig. 12).

It is thus only uncalcified or partly calcified tissue that can be permanently deformed following bending. A well-calcified bone will not be permanently deformed to any significant degree. As shown above, the alveolar bone of the rat may possibly be regarded as an exception to this rule. Stabilized by thick periosteal layers the deformed maxillary bone may have a tendency to retain its new form and position.

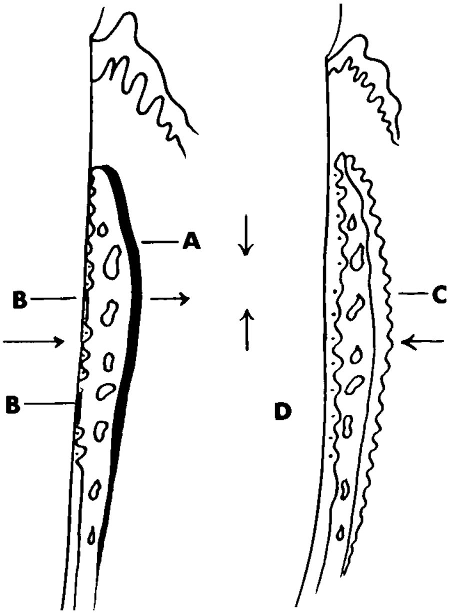

Fig. 12 Schematic drawing of bone deformation. Left: Dark layer, *A*, indicates degree of bone bending after bracket engagement has been established. *B*, compressed zones which will be eliminated by bone resorption. Right: *C*, compensatory bone layer bordering the labial bone wall which has moved back since space was created by bone resorption. *D*, root of the tooth.

CONCLUSIONS

1. A comparison of human and animal structures reveals that the lingual and labial alveolar bone walls of the dog and the rat are dense and contain relatively few marrow spaces, anatomical details which may influence the resorption process on the pressure side in experiments of longer duration.
2. Prior to tooth movement the alveolar bone of the rat is occasionally aplas-

tic or may be undergoing bone resorption. This lack of preformed osteoid tissue may cause a delayed bone deposition on the tension side as compared with the initial formative changes observed in human structures, the monkey, and the dog. Other variations observed in the rat are hyalinization starting after short experimental periods and periosteal undermining bone resorption on the pressure side.

3. The most conspicuous findings in the rat are the thick cementoid layers formed at the apical third of the root, deposition of endosteal osteophytes and, especially, the maxillary bone deposition which was observed in all cases after an experimental period of two days. The possibility exists that these bone layers could be the result of a bioelectric effect elicited by bone deformation.
4. Permanent deformation of uncalcified or partly calcified bone spicules was observed in the dog. In the rat deformation of the alveolar bone wall may possibly persist following deposition of thick maxillary bone layers. In man there is a tendency for a thin deformed bone wall to move back toward the root surface as soon as the periodontal space has become widened by frontal bone resorption.

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