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Tissue changes, particularly of the bone, incident to tooth movement

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The growing active interest for orthodontia, due to the manifold technical improvements of the appliances, and the tremendous impetus this specialty acquired through these improvements, accounts for the universal attempts to establish and to broaden, by means of scientific research, the principles of orthodontia empirically adopted. For the same reason I undertook the histological investigation of the nature of the tissues before, during and after tooth movement, to obtain eventually, from the resultant findings, new viewpoints for the practical application of orthodontia.

In so far as we are not able to give an accurate account regarding the changes occurring during tooth movement, we are unable to speak of any definite, scientifically confirmed procedure.

The theories pertaining to tissue changes incident to tooth movement hitherto advanced, are only hypotheses, which may probably explain certain phenomena but utterly fail in others; they are hypotheses that either entirely lack an anatomical or experimental basis, or rest upon wrong interpretations or wrong deductions. This may be due partly to the difficulty of the subject, and partly to the faulty technique of occasional experiments. The theories, hitherto advanced, relating to tissue changes incident to regulating, are based, on the one hand, on the old pressure theory of Schwalbe-Flourens [Angle, 1908; Hecht, 1900; Sandstedt, 1904, Schwarzkopff (Pfaff, 1906)], which supposes that there is resorption taking place on the side of the bone where pressure is applied, and deposition on the opposite side, where pressure is eliminated (whereby organic action of an increased pull has been regarded as the equivalent of elimination of pressure); on the other hand, the elasticity, the compressibility and extensibility of the bone, was accounted for in all changes of position of the teeth, a theory which was advanced by Kingsley (1881), and further elaborated upon by Walkhoff (1890, 1891, 1900,a,b).

The two theories, as may be observed, being diametrically opposed, I considered it as my immediate aim to ascertain, by my research work, which of the two may be the correct one. As I anticipate, I was led to the result that both theories cannot be made to agree with my investigations.

During my experiments I was striving to exclude all possible sources of error, and selected as my force producing implements the spring arch and wire ligatures, as prescribed by the Angle method. I was thereby enabled to estimate the application and control of force, and, through tooth movement, slowly and constantly produce effects in the bones and in the other tissues, which, during regulating in man must be similar, under like established conditions.

The questions, arising on the elaboration of this subject, may be formulated as follows:

1. Of what nature are the changes in the bony tissue;
2. Changes in the peridental (*sic*) membrane;
3. Changes in the tooth itself;
4. What is the reaction of the tissues during retention;
5. Conditions of the bone in different anomalies;
6. Eventual deductions for the practical application of orthodontia.

A baboon was used for the experiment, and the various tooth movements performed on the still firmly implanted deciduous teeth. The experiment was made on the teeth of the ape, because their structure is nearest that of man; because the straight course of the roots assures a most direct transmission of the operative force to the bone, and because, from the anatomical standpoint, there are in the ape analogous relations of the teeth to the compact and spongy bone of the jaws to those in man.

Owing to the difficulty of obtaining older animals with fully developed permanent dentitions, the experiments were conducted on the still completely firm deciduous teeth. Although the moved teeth exhibited phenomena of slight resorption it was proved by comparing them with the corresponding teeth on the other half of the jaw, which also exhibited such changes, that these resorptions were due to the following along of the permanent teeth and could not have been produced by the effects of the externally applied force. The pictures on hand are therefore unmistakeable evidence of the reaction to the effective force.

The movements performed were labial, lingual, depression, elongation and rotation; one half of the jaw being operated upon, while in the other half the teeth were left intact and employed as controlling factors.

The space of time in which the force was operative extended over 40 days; the photographs, therefore, demonstrate the results obtained after that period. The intermediate stages of the transformation of the bone, gained in a second series of experiments, will be given in detail elsewhere. The complicated conditions prevailing in rotation, especially the impossibility to cut sections for orientation as to the direction of the effective force, prevented me from reproducing such photographs. The treatment of the preparations from the fixation to the embedding into celloidin was accomplished in the usual manner. From the individual preparations, section series were made, paying special attention to have the cut made through the middle of the pulp; well orientated radial sections were conducted in the long axis of the tooth to correspond partly with the sagittal, partly with the frontal plane of the body. I have put special stress on the longitudinal radial sections, because the force applied was also in this direction. The preparations were stained partly with haematoxylin for the study of the changes in the bone, and partly according to Mallory for the investigation of the ligament apparatus. All movements may be traced to the simple push and pull; we are therefore concerned only with those changes resulting from the action of these forces.

As mentioned before, I shall now discuss more fully the tissue changes incident to the labial movement in particular. I will briefly point out on the illustrations on hand the analogous changes in the other movements — the lingual, the elongation and the depression. Likewise, will I also take into consideration the anatomical and histological relations of the ligamentum circulare [fibres of the gingival potion of the peridental membrane (dental ligament)].

Before I begin with the description of the individual movements and their instituted changes, I will show you briefly the principle of bone construction and bone destruction, which you are well acquainted with. As it is well known, the bone is built by cells, the so-called osteoblasts; as in the manner of the cells, be it through the transformation of their protoplasm (Waldeyer), be it through a sort of secretion (Gegenbauer), a question which has, up to the present, not yet been satisfactorily settled, they build the young bone substance. This young bone substance is not as yet calcified, the deposition of the calcium salts taking place at a later period. The growing bone during its further progress encloses a part of the osteoblasts, through which event the so-called bone corpuscles originate. The indications of new bone formation are therefore a kind of epithelium-like covering of osteoblasts arranged in rows and uncalcified bone substance (osteoid tissue) which surrounds the older bone in the form of a zone; and in the histological slice (Fig. 1). Due to the dissimilarity in affinity to the staining reagent it may easily be differentiated from the older calcified bone.

The indications of resorption on the histological slide (Fig. 2), are large polinucleated cells, giant cells (osteoclasts; von Kölliker, 1902), embedded in bays or recesses of the bone. These recesses, Howship's lacunae, are the result of activity of the cells.

Passing over to the discussion of the preparations, I would like to demonstrate to you first a section through the normal tooth (Fig. 3), in order to compare and to illustrate the existent changes in the other preparations; in its entire extent, from the alveolar border to the apex of the root, the labial wall consists of a simple layer of compact bone which shows clearly its lamellated structure; the lamellae run in the longitudinal direction of the tooth. The mighty masses of spongy bone on the lingual side of the tooth, especially those parts lying nearest the root, are also arranged in the longitudinal direction of the tooth. As we are concerned with young growing bone, we find the individual bone

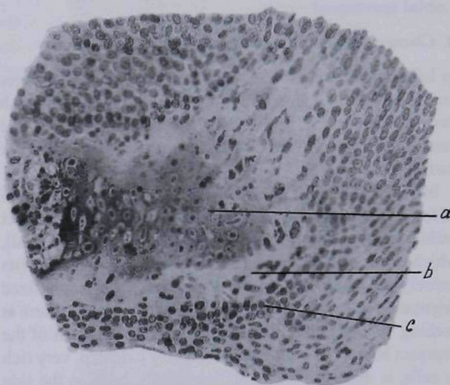

Figure 1 Histological slide of bone deposition. *a* old calcified bone; *b* uncalcified bone (osteoid tissue); *c* osteoclasts.

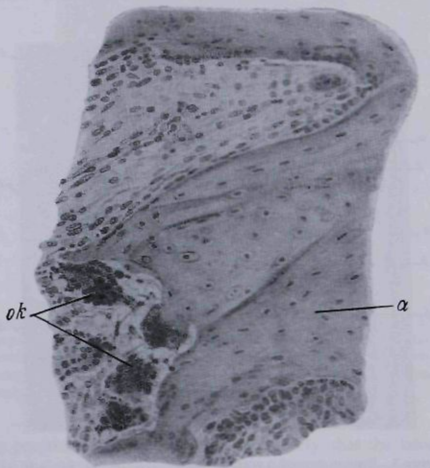

Figure 2 Histological slide of bone destruction. *a* old calcified bone; *ok* osteoclasts.

spicules in some places surrounded by osteoblasts, in the vicinity of which are also indications of occurring resorption, giant cells. The fibres of the peridental membrane, the so-called suspensory fibres, show the characteristic course, from the root obliquely upward to the bone. They are especially beautiful in the preparations stained according to Mallory (connective tissue staining; see Figs. 12 and 14).

This then would be a rough outline of the characteristic peculiarities of the normal preparation, upon which we shall have to fall back ever and anon.

Labial movement

A. Changes on the labial side, the side of the pressure

In labial movement of the teeth let us first test the changes on the labial side, the side of the pressure; we distinguish two surfaces on this labial wall; one toward the tooth, the inner surface, and one away from the tooth, the outer surface.

In Figure 4 we see the changes after 40 days application of force, i.e. at the end of our experiment. We find a perfect architectural reconstruction of the labial alveolar wall, which in the whole extent of its occlusal two-thirds, consists entirely of spongy bone spicules with their emphasized orientation vertically to the long axis of the tooth. There is nothing visible of the original lamellar arrangement of the compact bone. The young bone, scarcely calcified, very rich in cells, is densely beset with osteoblasts, both on the side toward the tooth as well as on the side away from it. The osteoclasts are visible only singly; the processes of deposition have, under the influence of long pressure, gained a decided advantage over those of resorption, which

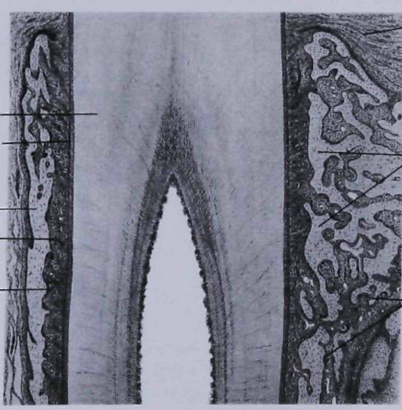

Figure 3 Section through a normal tooth.
On the left labial side; *a* dentine; *b* cementum; *g* peridental membrane; *l,k.* compact bone of lamellated structure; *ob* osteoblasts; *l,c* dental ligament; *k* spongy bone on the lingual side; *ok* osteoclasts.

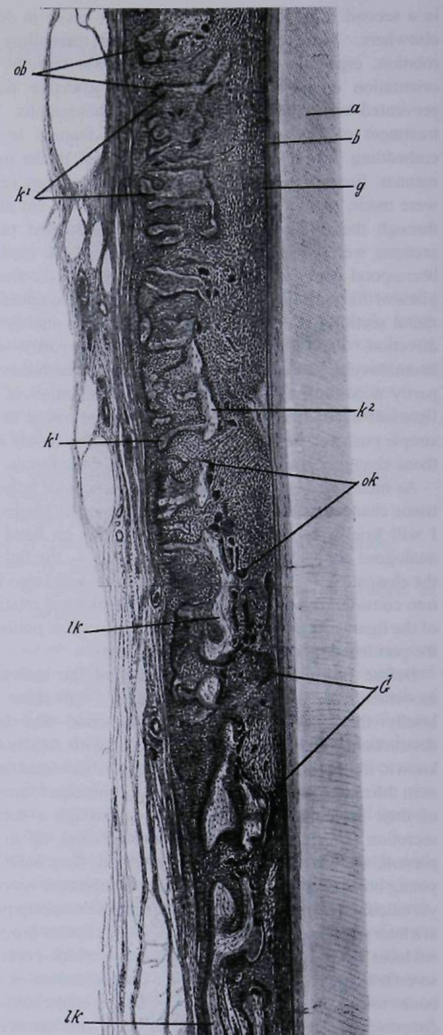

Figure 4 Labial movement; labial side; at *ob* near the alveolar border; the compact bone has disappeared and is replaced by spongy bone, with orientation of the spicules vertically to the long axis of the tooth. Between *G* and *ok* transitional zone. *a* dentine; *b* cementum; *g* peridental membrane, *G* blood vessels; *l,k* compact bone of lamellated structure; *ok* osteoclasts; k^1 new formed bony spicules beset with osteoblasts (*ob*); k^2 remains of compact bone, that has lost already the lamellated structure.

becomes noticeable in the enlargement of the bone. The bone possesses again its normal structure, the lamellae being arranged in the longitudinal direction of the tooth, in the third at the apical region of the root; it forms again true compact bone, which is undergoing resorption on the side facing the tooth; we find on this surface the osteoclasts extremely numerous on the transitional zone from the lamellated to the newly built spongy bone.

In that very place we can follow quite distinctly the transformation of the compact into the spongy bone. Just as in the normal preparation the compact bone in the apical third presents a dense single layer; toward the point of transition to the spongy form this layer becomes thinner, divides into partly longer and partly shorter single small disconnected spicules, which still exhibit lamellated structure; but as we depart from the root apex, they proportionately lose this character. At the same time buds spring from the bone surface away from the tooth, which become constantly denser and wider toward the alveolar margin, while the isolated compact bone spicules become proportionately constantly shorter and thinner, and finally disappear, to be completely replaced by the newly constructed cancellated tissue.

The peridental membrane is compressed almost in the entire length of the root, and presents only one-third (0. 9 mm) of its normal thickness (0-27 mm); its cellular elements are increased in number retaining their reaction to stains, and having their nuclei intact. No vessels have been demonstrated in the marginal half of the alveolar wall; whether these have actually disappeared or only collapsed, I could not determine. The vessels of the peridental membrane become visible again toward the apical half of the alveolus.

Haemorrhages may be found isolated in the tissue, in some places diapedes of the blood corpuscles through the vessel wall. Contrary to Sandstedt (1904/05), I could demonstrate no thrombosis either at the nearest proximity of or at any remote distance from the operative force. The staining property of the cells as well as the mitoses observed in various places enable us to realize the absolute vitality of the tissue, notwithstanding its compression to one-third of its original thickness.

The characteristic direction of the fibres of the peridental membrane is preserved unchanged. Also the fibres of the ligamentum circulare have suffered no disturbance.

In the cementum are found some recesses or bays of resorption which, in some places, reach into the dentine; but slight resorption bays may also be demonstrated in the cementum of the normal preparation, so that there is no special significance connected with this condition.

The preparation (Fig. 5), selected from another experimental series, where intense force was exerted for 30 days, i.e. almost the same length of time as of the one just discussed, furnishes us with valuable information for the practical application of orthodontia, as we shall amplify in

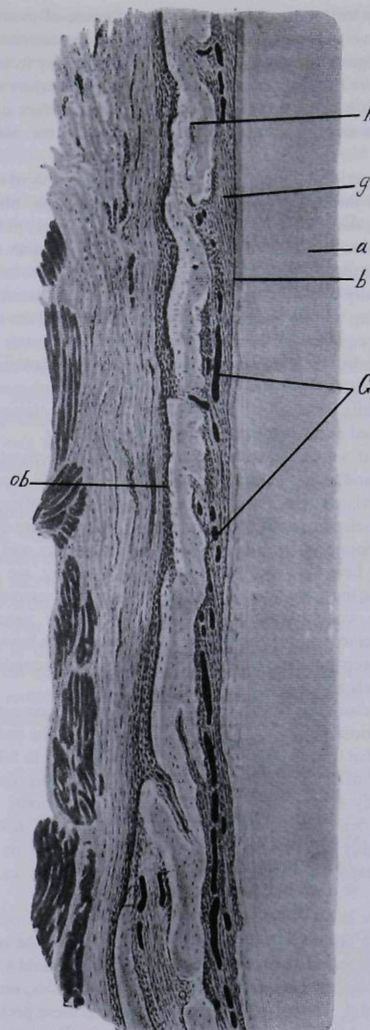

Figure 5 Labial movement; labial side; application of intense force. The compact bony plate (*k*) throughout somewhat attenuated; no architectural reconstruction; all vessels of the peridental membrane (*G*) filled up with homogenous masses (thrombosis?); *a* dentine *b* cementum; g peridental membrane; *ob* osteoblasts in sporadic layers.

the practical conclusions. We find namely, that the labial side, the side of the pressure, is entirely unaltered, except to an attenuation comprising the whole labial wall; the osteoclasts on the side facing the tooth (as was demonstrated in all other preparations, under the influence of pressure) appear very sporadic. Similarly striking is the entire absence of all signs of bone formation on the surface away from the tooth; we find the osteoblasts in very sporadic layers only. There is nothing visible of any budding; the surface of the bone is smooth as on the compact bone of the normal tooth.

The peridental membrane, compressed to one-third of its normal thickness, presents a cell-meagre, tough, fibrous tissue; whether the serious alteration of all vessels present thromboses occasioned during life or whether the homogeneous masses, filling up the vessels, are caused artificially by the influence of chemical reagents as used in preparing the specimens could not be ascertained for sure; in consequence of the small diameter of the vessels and considering their compression caused by this movement, the unmistakable criterions of the intravital thromboses are most difficult to identify and could also this picture be explained as the result of a vascular engorgement.

But if we take into consideration that all preparations were handled in the same manner, that all animals died by haemorrhage, which necessitates a relative haematology of the vessels like in all other preparations, that this state could not be found among any of the other preparations, and that exactly here the reaction of the bone is missing, we can, based on these theoretical considerations and in consequence of the work of Bum, who pretends that a vascular engorgement promotes the growth of bone, which however in our preparations is entirely missing, explain this condition of vessels as disturbances of circulation.

No resorption recesses can be shown in the cementum. The periosteum on the lingual side, the side of the pull, is somewhat broader, the tendency of the bone being to follow the pull of the fibres, to respond with bone building, not so markedly emphasized as in the other preparations. The above described alterations of the vessels are not so thoroughly pronounced as on the labial side, but on the other hand do we find numerous haemorrhages in the tissue.

While the phenomena of resorption of the bone on the one side do not by far reach the intensity as on the other preparations, and we can only demonstrate a general slight attenuation of the compact alveolar wall, we miss, on the other hand, all new bone formation and find these peculiar conditions of the vessels of the peridental membrane, which by further investigations must be more minutely explained. In any case the perforation of the compact bone by the vessels at different places has also its reason and needs further explanation (sign of resorption).

The hypothesis therefore may be founded, that there is some relation between the absence of new bone formation and the alteration of the blood vessels i.e. that thus the vitality of the periosteum is so far reduced, that it is in no condition to respond to stimuli and build new bone. These conditions are, according to my belief, the result of the trauma, caused by the too fast and intense movement of the tooth.

B. Changes of the lingual alveolar wall

The pull exerted on the tooth is transmitted to the bone through the fibres of the peridental membrane. We find there, on the side of the pull, just as complete as characteristic changes. The architecture of the bone has experienced, as observed in Figure 6, total reconstruction, and shows a complete deviation from the normal preparation; the characteristic differences are best obtained by comparison with the architectural construction and arrangement of the spongy bone spicules in the normal preparation (Fig. 3). They consist, especially in the gingival half of the root, of the original massive spongy bone spicules, which are mostly arranged in the longitudinal direction of the tooth, being transformed into narrow, long bone spicules, arranged in the direction of the pull, i.e. they are transformed into bone spicules arranged vertically to the long axis of the tooth.

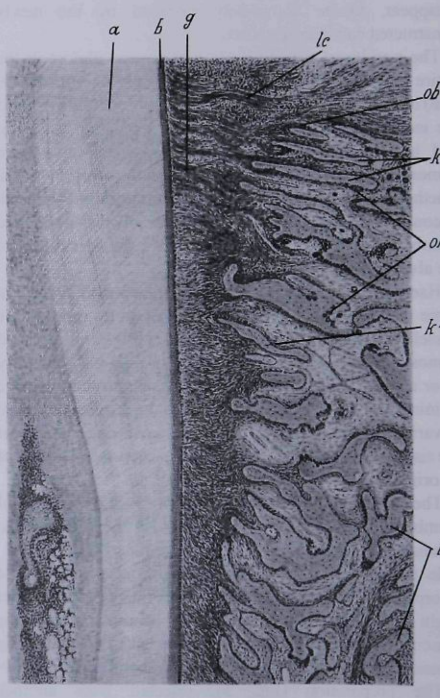

Figure 6 Labial movement; lingual side. The bony spicules in the third near the alveolar border present long spicules with orientation vertically to the long axis of the tooth (k^1), densely beset with osteoblasts (*ob*). *a* dentine; *b* cementum; *g* peridental membrane; *lc* dental ligament; *k* old bone; *ok* osteoclasts.

The ends of the spongy bone spicules directed to the tooth are densely beset with osteoblasts, and show uncalcified zones, indicating growth in length and breadth of each spicule. On the end of the spicules directed away from the tooth, we find quite numerous osteoclasts and phenomena of resorption.

So we prove active bone formation on the side of the pull, especially in that portion of the bone lying in the proximity of the alveolar border, while the bone enclosing the root end shows no essential changes, either on the labial or on the lingual side.

The periosteum is somewhat thickened at the alveolar border and acquires its normal thickness toward the middle of the tooth; the nuclei have preserved their staining property. Mitoses are rarer to find here than on the labial side. In close contact with the new formed bone we find slight haemorrhages in the tissue; thromboses could not be demonstrated. Only toward the root apex do we find again normal conditions.

The characteristic arrangement of the fibres is entirely preserved as well on the labial as on the lingual side.

Several shallow bays of resorption could be found in the cementum. The fact of the broadening of the periosteum on the lingual side is of significance in the question of retention, and we shall discuss it more minutely later, in the practical conclusions.

In the following pictures we will find the changes produced by other movements. In spite of the variety of movements, we will always demonstrate the same characteristic manner in which the pressure and pulling reaction of the bone appear, and I will only briefly refer to the attendant phenomena of the other involved tissues.

Lingual movement

A. Changes on the lingual side, the side of pressure (See Fig. 7)

As on the labial side in the labial movement (Fig. 4), we can easily demonstrate also here, that, under the influence of the same force, analogous changes took place, that of the original bone structure nothing can be observed, and that a complete architectural reconstruction of the bone occurred.

Similarly, as in Figure 4, do we find after 40 days application of force a preponderance of the processes of deposition over the processes of resorption. The individual newly formed bone spicules, particularly those at the gingival third, have arranged themselves in the direction of the force, i.e. perpendicular to the long axis of the tooth. The ends of the spicules directed toward the tooth, i.e. the ends subjected directly to the pressure, show broad, uncalcified zones which are surrounded by densely arranged rows of osteoblasts, presenting, as it were, the indication of the most active bone formation. At the ends of the spicules directed from the tooth we find occasionally numerous osteoclasts.

These changes appear classical when compared with the normal preparation (Fig. 3).

No deviation from the normal photograph could be demonstrated in the periosteum, which is distinguished by being compressed to one-third of its normal thickness, except in the gingival third, where the vessels are compressed. Haemorrhages and thromboses could not be shown.

No changes could be demonstrated either in the cementum or in the gum. The jamming and the resultant puffing of the gum, referred to by some authors on the lingual side of the teeth during their lingual movement, is only the effect of too rapid and intense movement; I could point out neither macroscopic, nor microscopic changes at all.

B. Changes on the labial side, the side of pull (Fig. 8)

The labial wall (Fig. 3), which normally consists of lamellated bone — the lammellae being disposed parallel to the long axis of the tooth — has undergone a complete architectural transformation under the influence of the pull. The compact bone lamellae in the region of the alveolar margin is considerably thickened by the new formed spongy bone, formed under the influence of pull; its spicules assumed in many places a perpendicular direction to the long axis of the tooth, i.e., in the direction of the pull. The bone is thickened in its entire extent. It reaches its maximum at a point below the alveolar border (0.54 mm against 0.27 mm in the normal preparation); but gradually decreases toward the root apex without at any point presenting the slenderness of the compact alveolar wall of the normal preparation.

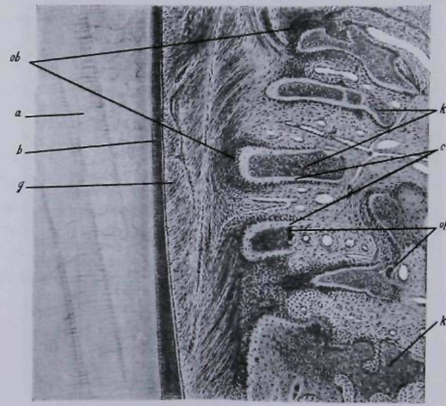

Figure 7 Lingual movement; lingual side. Near the alveolar margin the bone spicules (k[1]) arranged in the direction of the force, surrounded by uncalcified zones (*o. G.*) and densely arranged rows of osteoblasts (*ob*). *a* dentine; *b* cementum; *g* peridental membrane; *ok* osteoclasts; nearer to the apex of the root old unchanged bone (*k*).

At the middle, and particularly at the apical third, we find as yet compact bone, from the surface of which, spring strong spicules toward the tooth. In the gingival third we find only spongy bone, of which the spicules show active bone construction on the side toward the tooth. In parts more toward the root, on the bone surface next to the tooth, we find now and then numerous osteoclasts. The external surface of the bone is smooth and shows no indication of resorption. We have here the classical picture of the reduction of the compact bone to its original element, the spongy bone (Von Meyer, 1867).

The bone surrounding the root apex shows no essential changes either on the labial or on the lingual side, which would indicate the influence of pull or pressure.

The periosteum, somewhat thickened as compared with the normal preparation, shows no particular deviations from the normal in regard to the number of cells, blood vessels and course of the fibres; haemorrhages and thromboses are just as little demonstrated.

Elongation

The most pronounced changes in this movement are found in the spicules of the spongy bone at the bottom of the alveoli and near the alveolar border, for the pull exerted through the ligamentum circulare and the peridental membrane influence, above, all these bony spicules.

We see, therefore, at the alveolar border, as well on the labial as particularly on the lingual side (Fig. 9), the elongation of the spongy bone spicules in the direction of the pull; these spicules are surrounded by a strong zone of osteoblasts. The spongy bone spicules at the root apex appear as long, thin, buttresses, stretching from the depth toward the root apex; their tops and sides being enclosed by narrow uncalcified zones and strong layers of osteoblasts (Fig. 10). The bone relations at the root apex of a normal tooth are presented again in Figure 11.

The peridental membrane shows no essential changes on the labial as well as on the lingual side. A breaking or greater stretching of the fibres could nowhere be discovered; in some places there may be found some slight haemorrhages which become more numerous toward the root apex; no thrombi. The most essential change refers to the thickness of the peridental membrane which is almost twice the diameter of the normal preparation in the lower half of the root. The cementum remains unchanged.

Depression

The reaction of the bone to the pressure below the root apex, could not be demonstrated in this movement, owing to the too great approximation to the permanent tooth germ; but also on the spongy bone spicules on both sides of the root, could the typical pressure changes upon the spicules not be confirmed throughout, but only on the third towards the

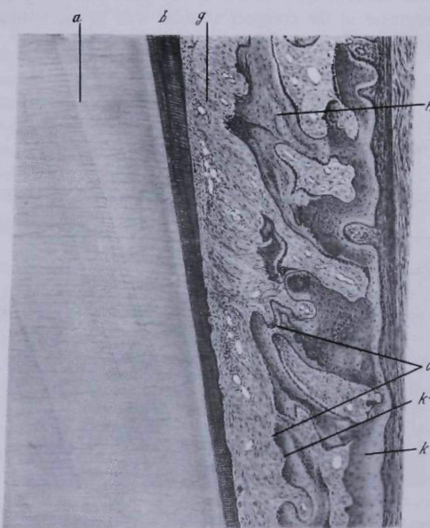

Figure 8 Lingual movement; labial side; at *a*, *b*, *g*; near the alveolar margin. *k* compact bone; k^1 new formed spongy spicules; *a* dentine; *b* cementum; *g* peridental membrane; *ob* osteoblasts.

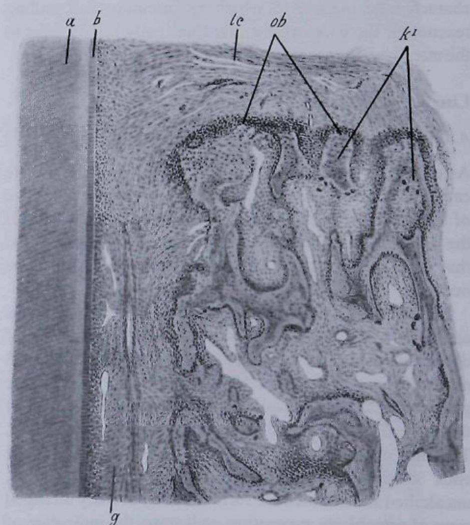

Figure 9 Elongation; lingual alveolar margin. k^1 new formed spongy bone spicules, elongated in the direction of the pull; *a* dentine; *b* cementum; *g* peridental membrane; *lc* dental ligament; *ob* osteoblasts.

alveolar border. For these relative slight reactions of the bone we can possibly hold responsible the serious traumatic changes of the peridental membrane and their consequent lowering of the reactive capacity of the bone.

About a 'compression of the spongiosa' and a 'diminution of the marrow spaces' there could be seen just as little here as in the affected side in labial and in lingual movement.

In order to follow, on the one hand, the structural relation of the alveolar septum, and on the other hand, the constant demonstrable co-movement, i.e. inclination of the adjacent teeth, we had to bring into our section the shortened tooth (the lower central incisor) as well as its adjacent tooth (the lateral incisor); the section had, therefore, to be made in the frontal direction. The visible symmetrical relation of both teeth to the septum of the normal preparation, the two incisors of the other side (Fig. 12) is in the pathological preparation (Fig. 13) so greatly modified, that the septum here is pushed entirely toward the side of the unmoved tooth. There is no reconstruction in the direction of the pressure noticeable in the spongy bone spicules on the upper margin of the septum which is displaced by the ligamentum circulare. The elastic pressure of the ligamentum circulare may possibly be made responsible for the fact that we do not find here similar changes as in the pressure transmitted through the rigid mass of the tooth (orientation in the direction of pressure) but merely a proliferation only of the osteoblasts on the spicules nearest the ligament. The further distant bone spicules are in a condition of rest, and we find only individually dispersed osteoclasts in the tissue.

The periosteum, as well as the ligamentum circulare, show individual noteworthy changes. Regarding the thickness of the peridental membrane we find the relations so far changed, that due to the original symmetric position of both teeth to the septum, the thickness on both sides amounting to the same, is now on the side of the shortened tooth two-thirds and on the other side one-third. This is brought about by the displacement of the septum toward the normal tooth through the pressure of the ligamentum circulare. The fibres of the ligamentum circulare firmly fixed onto the cementum of the shortened tooth, as well as onto the neighbouring one, have sunk with the shortened tooth, and show an oblique direction upward toward the cementum of the unmoved tooth (Fig. 13).

The direct course of the ligamentum circulare from one tooth to the adjacent one, transversely across the septum, has until now not been sufficiently emphasized, at least in the German literature. We find universally asserted that the 'bundles arising from the alveolar border radiate obliquely toward the cementum at the neck of the tooth and so form, under the enamel margin, a ring-like union of the tooth and the alveolar margin, the 'ligament circulare' (von Kölliker,

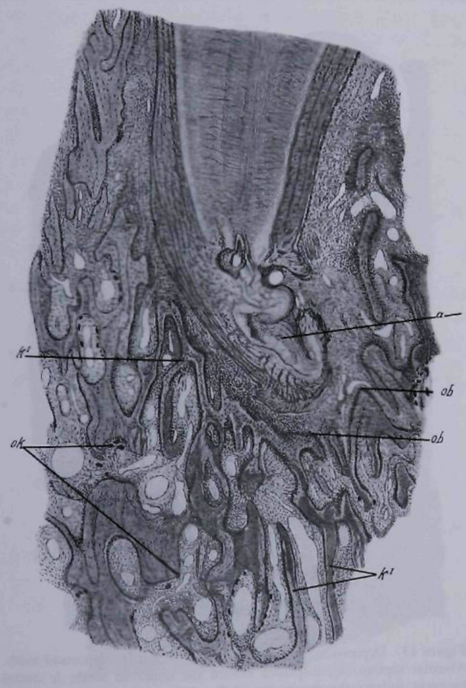

Figure 10 Elongation; apex of the root. k^1 in the direction of the pull orientated long bone spicules, at their tops, looking towards the apex, enclosed by strong layers of osteoblasts (*ob*); *a* root apex; *ok* osteoclasts.

Figure 11 Region of the root apex; normal slide. *a* tooth; *k* bone; *ok* osteoclasts.

1902; Stohr, 1889). This may be attributed to the labial and lingual surfaces of the tooth; on the proximal surfaces, however, the above described condition – the direct course from tooth to tooth is demonstrable (see Fig. 12). For the purpose of a more favourable demonstration of these relations this preparation is stained according to Mallory (connective tissue staining). The same condition is found in human teeth (Fig. 14). I found a corroboration of the same by Subirana Matas (1909) and Noyes (cited in Kirk, 1905).

A complete description of the normal conditions of the peridental membrane would only be a repetition of something familiar, and we can therefore recommend the thoroughly elaborated treatise on this subject by Noyes. The interrelation of the teeth through the firm bundles of fibres running transversely across the septum is, to us, of the greatest practical importance, and shall later be more thoroughly considered.

While we have already repeatedly emphasized the tremendous power of resistance of these fibres, we cannot claim this of the other, the more deeply placed parts of the peridental membrane – the suspensory fibres of the tooth. We find occasionally such changes as prevent us from distinguishing the structure and course of the fibres. The fibres, which are severed partly from the cementum and partly from the bone, lie in disorder, and are often visible in a transverse section. The resistance of these fibres being once destroyed or they being partly torn or partly resorbed, the entire elastic resistance which prevents the tooth from shortening, rests then with the ligamentum circulare only; the vessels of the peridental membrane do not find sufficient protection from compression by the advancing root; thus are explained the serious haemorrhages in the entire peridental membrane and especially at the apex of the root. The vessels entering the dental pulp must similarly be injured; at any rate, this histological condition often finds its verification in the clinical picture, in which very often sensitivity and looseness of the teeth result from these also slowly conducted tooth movements. These serious changes could be demonstrated notwithstanding the most careful and most cautious application of force. The fact that even in

Figure 12 Frontal section through two incisors; stained according to Mallory (connective tissue staining). *a* alveolar septum; *g* peridental membrane; *lc* dental ligament, transversely across the septum from one tooth to the adjacent one, uniting them firmly; *c* gum papilla; *Zk* germ of the permanent tooth.

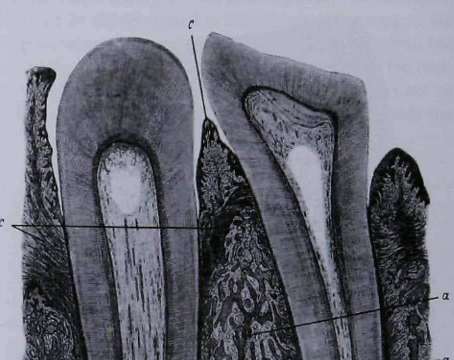

Figure 13 Depression; frontal section; on the left the depressed tooth. Alveolar septum (*a*), displaced toward the unmoved tooth; *lc* dental ligament follows the movement of the depressed tooth; *g* peridental membrane; *g′* by haemorrhages and ruptures of the fibres pathologically changed peridental membrane; *h* germ of the permanent tooth; *c* gum papilla.

this movement, though endangering the vitality of the pulp, comparatively few devitalizations can be demonstrated (such cases have been recorded), is explained by the abundant supply of blood vessels in the periosteum and numerous collaterals (Demointporcelet and Decaudin, 1887), but I cannot testify this statement.

The cellular elements have as a whole somewhat increased; near the root apex there are individual resorption recesses which extend into the dentine. Owing to the intimate relation through the ligamentum circulare it is quite plain that we find changes in the adjacent tooth, though only slight, which are indicated by a co-shortening or inclination of the tooth.

To recapitulate the results of the histological findings thus far described, we can frame them in the following sentences:

The bony tissue, be it compact or cancellated, reacts to pressure by a transformation of its entire architecture; this takes place by resorption of the bone present and deposition of new bony tissue; both processes occur simultaneously. Deposition finally preponderates over resorption. The newly formed bony spicules are arranged in the direction of the pressure. Increased pull has similarly

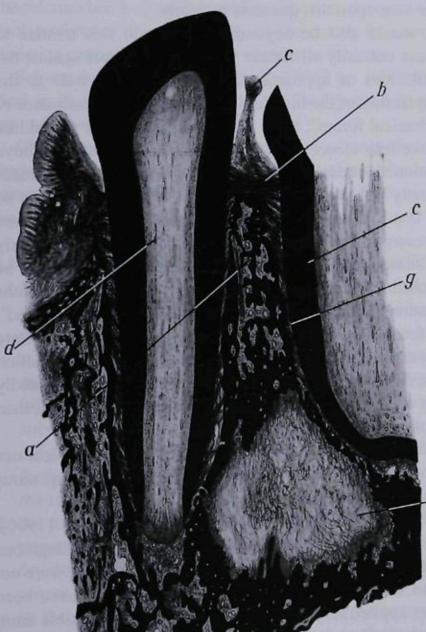

Figure 14 Frontal section through two incisors in man; stained according to Mallory. *a* alveolar septum; *b* dental ligament; *c* gum papilla; *g* peridental membrane; *h* germ of the permanent tooth.

addition of new bony tissue as a result, and simultaneous orientation of the spicules thereof in the direction of the pull. This rule I could not demonstrate in one preparation only, on the labial side during lingual movement (Fig. 8). What conditions this may be attributed to, I am as yet unable to explain.

The entire transformation of the architecture and the orientation of the newly formed spongy bone spicules, always occur so characteristically and lawfully, that we can say by the histological preparations in what manner the movements were accomplished.

This characteristic transformation results only upon the application of very slight, physiological-like influences. Should the force be too strong, the result will be such serious injuries to the periosteum, due to the disturbances in circulation, that there will be no typical reaction of the bony cells.

'The newly formed bony parts may and must originate from any convenient connective tissue that is accidentally placed in any position in the direction of which the pressure or pull is exerted.' (Wolff, 1872).

Any force applied during the movement of the teeth is withstood by the fibres of the ligamentum circulare, indeed, they at times hypertrophy in an attempt to justify any higher demands made upon them. The fibres of the periosteum below the alveolar border, extending to the root apex, show no uniform relation: while they at times retain their regular course during the application of external forces, we find them disturbed in other photographs, at times hardly more than just a suggestion.

The vitality of the periosteum suffers no injury during the application of 'physiological forces', even on compression of the same to a third of its original thickness. It may be exposed to slight haemorrhages, to occasional constriction in the lumen, disappearance of the vessels; but the staining ability of the cell nuclei is retained, and no disintegration can be demonstrated by any photographs.

The teeth themselves undergo no changes.

The recesses of absorption observed on the cementum of the root, are found as well on the moving teeth as on the controlling teeth, and as we were dealing with milk teeth we cannot preclude the possibility that we are already in these cases confronted with the beginning of the processes of resorption of the roots of the deciduous teeth.

Changes in the cementum and gum tissue could not be demonstrated.

If we now compare the results of my investigation with the theories of the other authors, briefly mentioned in the introduction, we find that these theories are all in direct opposition to my findings. On the other hand do they completely coincide with the law of transformation of the bones advanced by Wolff (1892), and form an objectionless verification of this law, as well as the indubitable refutation of the pressure theory (Beneke, 1897; Wolff, 1899).

Nowhere in the bone system can we prove better the correctness of the Wolff law than in the jaw bones, for in no bone of the human skeleton have we at our disposal such favourable conditions for the direct application of force as in the jaw, e.g., through the medium of a peg, the tooth, implanted in the bone.

The corroboration of my reported findings based on the last works on bone transformation, I shall reserve until the publication of the intermediary stages in bone transformation, obtained from my experimental series. This publication allows space only for short information of the most important actual findings.

Before entering the conclusions in relation to the practical application of orthodontia, I will briefly critically discuss the theories hitherto advanced by other authors regarding the processes occurring during tooth movements as far as I had occasion to examine them.

Kingsley (1881) assumes that resorption and deposition takes place only in slowly performed movements and that in quick movements the elasticity of the bone only comes into consideration; the bony lamellae are displaced together with the teeth 'retaining thereby their entire integrity and functional ability'. These suppositions of this well renowned observer, based only on clinical experiences, may only be appreciated as theoretical deductions and combinations.

The theory, stated by Walkhoff (1890), *viz.* 'that a movement of a tooth consists in the creation of different tensions in the bony tissue, its consolidation in the compensation of these tensions' is also the result of theoretical deductions, based on practical observations and on the inability of explaining many facts of the practical orthodontia by the pressure theory. Walkhoff's theory, which only admits a transposition but no transformation of the histological elements (Walkhof, 1891), is based on the theory of the elasticity, flexibility and compressibility of the bone and on the assumption that the bone and the teeth can only be influenced on account of these mentioned peculiarities.

It is true, that each bone possesses a certain degree of elasticity — otherwise we would in extractions experience many more fractures of the bone as this was really the case. The elasticity however should in regulating be of no, and if so, of quite a secondary importance, for we must allow sufficient time for nature to follow our efforts by aiding her but should not pride ourselves having widened an arch within a few days for several millimetres or of having shifted backwards prominent teeth to still a greater distance.

Walkhoff (1890) endeavours to prove the impossibility of bony changes based on resorption and apposition and caused by orthodontic procedures by his statement 'that the alveolar process in regard to its thickness never undergoes any changes' and that the long space of time, often extended for years, necessary for bone transformation, is in no relation whatever to the short time, in which we often succeed to bring about great changes in the position of the teeth as well as in the shape of the jaws. Both these statements are refuted by my experiments. For, already after 5 days' application of force (perhaps still earlier) we found distinct signs of the incipient bone transformation (the respective communication will be published, as already mentioned, elsewhere) and could see that the thickness of the bone is undergoing quite considerable changes.

Also in a later pamphlet, Walkhoff (1900a) pretends 'that the application of pressure does not permit any apposition or transformation of the bone during the active period of force application' and concedes to the bony cells a formative activity only during the time of retention (law of transformation).

In another paper, Walkhoff (1900b) again compares the bone formation with the formation of a callus, in order to prove 'that osteoid tissue has nothing to do with tooth movement. If we were to remove the retaining devices already after a few weeks from corrected protruding front teeth like from a fractured bone after the formation of a callus, we had only to deal with failures'. But formation of a callus and transformation of the bone are processes, which cannot be compared with each other. It would go too far to enter here upon this question minutely.

It would also be beyond the frame of this treatise to discuss critically all further proofs of Walkhoff against the possibilities of apposition and resorption as well as the 'adaptability of the histological elements to the influence of mechanical forces'; there is only one question I would like to take into closer consideration on account of the above mentioned course of the fibres of the dental ligament (directly from tooth to tooth), that is his statement: 'if it be true that in closing a diastema between the central incisors the resorption on the mesial surfaces goes on simultaneously according to the deposition on the distal one's, it would be impossible, that these teeth part again after 6 months retention, though all mechanical influences were eliminated'. But for this I would rather make responsible (as I will more fully explain in the practical conclusions) the strong traction of the fibres of the dental ligament, which run uninterruptedly from one tooth to the other across the alveolar septum, than apposition and resorption.

Walkhoff's theories are based neither on anatomical nor histological researches but on theoretical though ingenious considerations and deductions.

The severe changes, referred to by Hecht (1900), consisting in ruptures of the bony spicules and cartilaginous transformation of the bone, surrounding the tooth, were not found in my specimens. There must certainly have been forces applied surmounting extensively the admissible limit. Generally Hecht advocates the pressure theory of Flourens and his statements mostly based on clinical observations. For his histological statements, only given in the description, I cannot find any explanation.

Angle (1908) assumes a bending of the alveolar process according to age, force and its direction, but in the sense that he assumes resorption by pressure and traction, while apposition simultaneously arises for filling up the hollow spaces, though slower progressing; therefore the necessity of a long retention up to the completion of bony deposition and formation of a new alveolus. The changes occurring in the different movements are explained as owing to the pressure theory.

Among the works treating on this subject, which I had occasion to examine, were the investigations by Sandstedt (1904), being however only preserved in fragments. Sandstedt is the only author forming his opinions based on experiments. It is remarkable that he confirms Flourens' pressure theory. The change of the connective tissue into hyaline as stated by him to be caused by pressure, as also the ever present thromboses of the vessels in close vicinity of or farther removed from the operation area, I could not confirm. There may be probably responsible for the result of his experiments the application of too great forces and consequently too strong an alteration of the tissues, followed by alterations of the vessels similar to those shown in one of my preparations. Nor was it possible for me to confirm Sandstedt's statement that in tooth movements we have to deal with a double armed lever, the fulcrum being about the middle of the root, the apex of the root performing the movements of the crown in a reverse direction causing corresponding changes in the bone.

Schwarzkopff's treatises (Pfaff, 1906) on this subject deal in such a general way, that we hardly need to enter upon their closer study.

Giving space now for the information of only the most important conclusions derived from the above described statements in relation to the practical application of orthodontia, we can compress them in the following sentences.

1. The apparent ever characteristic reconstruction of the bony tissue incident to tooth movement, manifests the urgent demand of taking into particular consideration the manner of procedure before beginning each treatment, in order to avoid practically any change in an already initiated movement; for the entire bony part, influenced by the existent movement, being thereby subjected to the necessary repeated reconstruction, can only signify retardation and injury to the final bone formation and may surely be made responsible for many failures.
2. As the periosteum is compressed on the side of the pressure, and thickened on the opposite side, i.e. the developing buds, due to the movement of the tooth, cannot follow so fast, it follows that the advantage gained by the slowest possible movement is foremost to avoid a too great loosening of the tooth, which is then always enclosed by bony tissue on all the sides; we gain furthermore, for the same reason the advantage of a shorter period of retention.

In rapid movements the periosteum is thus injured by haemorrhages, tearing of the fibres and disturbances in circulation, that it does not posses sufficient vital energy to respond normally to mechanical stimuli as we could see in the depression and much more drastically in the labial movement (Fig. 6). A tissue thus injured requires a long period of time to regain its normal physiological condition and thereby the possibility to react to the functional stimuli and to transmit them to the bone in the form of transformation. A lasting injury of the tissue may at times be left in the form just indicated, which Angle also points out in his work. We, therefore, do not reach our goal by fast movement or by application of powerful forces, on the contrary, we only retard the occurring processes of transformation necessarily influenced by function during retention, and we must expect imminent failure on the removal of the retaining devices, though under normal conditions this period of retention would have been sufficiently long. These contentions coincide completely with the observations and the clinical experiences.

In children and in young patients we are able, to a certain extent, to obtain the desired result by the application of more powerful forces, though at the expense of the considerable elasticity of the bone. In older patients, where this inherent elasticity of the bone is reduced to a minimum, we can at first also obtain results, which, however, will be in proportion with the still existent elasticity of the bone and the compression of the periosteum.

The entire procedure of such movement encounters great difficulties, and, indeed, fails to make any progress even upon the exertion of the most powerful forces. We can attribute this phenomenon to the lowering and consequent destruction of the vitality of the periosteum, to the thereby conditioned absence of transformation of the bone, which is a constant accompanying phenomenon of every change in position of the teeth.

Yet another motive for the avoidance of rapid movement upon the application of powerful force, is of great importance. When we have moved a tooth slowly, it will, after removal of the appliances, to a certain extent, but not completely, return to its original position; bone transformation has already set in, partly also due to the influence of functional stimulation.

This transformation we cannot expect in rapidly accomplished movements; we produce, on the one hand, serious traumatic changes, and on the other hand, on account of the elasticity of the bone, the tooth must quickly return to its original position.

From the reason shown above, then, the slower the movement is accomplished, the slighter will be the looseness of the tooth. The firmness of the tooth, during the process of movement, will then be our criterion for the correctly measured force. The macroscopic, of course imperceivable, thickening of the bone wall following slight pushing or pulling forces will explain the fact that teeth, greatly displaced lingually, may be moved labially or buccally, as the case may be, to a considerable extent without fear of dangerously attenuating the bone wall, besides very thin, an occurrence which may take place on roughly applied forces as I have had occasion to observe in two cases.

Hence the demand in encountering great resistances not to increase the forces but to prolong the time of their influence. Impatience for obtaining evident results is the orthodontist's greatest enemy.

3. Grünberg's teaching, as pointed out since years by way of his experience, *viz.* that in 'elongation' and 'depression' of teeth we have not to deal with their actual elongation or depression, but with an influence of the alveolar process, has now found an unmistakable confirmation; by the influence of the forces acting in the above mentioned way we have to deal with an apposition and resorption of the alveolar process. The length of the crowns does not undergo any change during these movements.
4. The standpoint is not correct, as held by many authors, that the tooth represents a two armed lever with its fulcrum at the alveolar border or at the middle of the root, and that on labial movement of a tooth, for instance, there must be bone resorption at the labial alveolar border and also on the lingual side at the root end. The tooth represents a one armed lever and the apex of the root serves as the pivot point or centre of motion. I could point out the changes influenced by the movements in the preparations almost throughout the entire length of the root, decreasing, however, in intensity from the alveolar border to the root apex. In the bone of the immediate proximity to the root apex there were no changes observable.

   Owing to the setting in of a complete transformation of the bone immediately upon the application of force, we cannot conceive of any fulcrum that would influence the root apex. This would only be possible upon the establishment of an artificial fulcrum, as is intended by the utilization of the appliances of Case and the working retainer and new appliance of Angle, if we would not leave to nature the normal placing of the roots and the normal construction of the entire architecture of the bone through the stimulus transmitted to the bone by function.

   The pronounced angle of inclination following extensive labial movement of the front teeth is solely a result of a forward movement of the crown, but not that of recession of the root apex. The root apex itself does not change its position.
5. The powerful interproximal connection of the teeth established by the fibres of the ligamentum circulare is of greatest significance in the instance of the occurring or intended co-movement of the teeth and the rapid return of some, particularly mesio-distally, accomplished movements. This appears singularly striking during the treatment of the diastema between the central incisors. In spite of the localized pull on the central incisors we may often succeed to close at times a considerable diastema without thereby creating a space between the central and lateral incisors or between the last and the canines. When these diastema also appear, they are so insignificant as not to be compared with the one closed between the central incisors.

   These powerful fibres stretching across the septa, giving off strong bundles partly to these and partly to the gums, prove to be the most resistive tissue with which we are dealing in our operations. Indeed, we find that the individual fibrilli gain in strength and number upon the stimulation of these fibres. The bone must yield to its force – must follow its pull. Also the intact persistence of the complete gum papilla, whose great value for the maintenance of the teeth cannot be sufficiently appreciated, can only be guaranteed by the integrity of these fibres stretching across the septa.
6. On account of the subtle reactive ability of the bone to external influences, as repeatedly emphasized, only upon the application of the mildest forces, the oft repeated argument as to the advantage of either the gradual and continuous effect of the spring or the unelastic rigid screw, can only be decided in favour of the former.
7. I would like to conclude the practical conclusions with the reference made by Grünberg during the discussion at the annual meeting of the European Orthodontia Society in Vienna. Namely, that the theoretical proof of retention has gained its foundation by these investigations. And the duration problem is meanwhile theoretically determined: We must retain so long until the bone concerned is functionally orientated again under the influences of the normal function.

In the supplement to this preliminary impartation, to appear shortly, I hope to be able to give a more exhaustive reply to the various questions hitherto advanced and here briefly treated. While the answers to the questions under 4 and 5 (the reaction of the tissues during retention, and the condition of the bone in different anomalies), I shall reserve until a later period, owing to the necessity for further investigation.

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