The Periodontal Membrane in Function*

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PREFACE

SCIENCE is traditionally divided into two parts, physical science and biologic science. Such a division was quite a natural one from the point of view of early investigators, for what more obvious division could be found than that between the worlds of the inanimate and the animate? But, with the passage of time and the accumulation of more exact data, this sharp distinction between the two has become less apparent.

The laws of physical science, though they have been discovered and studied in the inanimate world, are actually universal in their application. They apply just as well to the functions of living things as they do to the simplest machine. The only difference is that the living world presents such a complicated picture that physical science of necessity had to begin investigation with the simpler and more easily controlled inanimate subjects.

The biologist also began with the simplest cases which he could find; first gross anatomy and then the functions of individual organs and systems in their simplest manifestations as exhibited in the lower forms of life.

Each group has conquered successively more difficult problems until now the physical scientist actually encroaches on the territory of the biologist, analyzing enzymes and measuring electrical currents in the brain. Now the picture is beginning to assume its true form. Biology is no longer a science set aside by itself but has actually become a part of physical science. The biologist has come far in his investigations of the all-important end results of the complicated physical processes which are life; but it remains for the physical scientist ultimately to bridge the gap and tell us why and how these results are brought about.

In view of all of this it is important that the biologist recognize the situation and take advantage of it. He must be ever on the alert for opportunities to increase the fruits of his own work by the application of knowledge from other branches of science. The scientist should not be found guilty of merely describing what he sees in his microscope when the means are at hand for analyzing, interpreting and applying it.

The subject of study in this paper, the periodontal membrane, is a living organ familiar to everyone associated with the science of dentistry. It is without apology that this membrane is now dissected and studied from a physical viewpoint in an attempt to learn some of the basic laws which underlie its construction and the influence that they may have on its clinical behavior.

* The opinions and assertions contained in this paper are those of the writer and are not to be construed as official or reflecting the views of the Navy Department or the naval service at large.

Survey of the Literature

The literature on the periodontal membrane is voluminous, but that dealing with the actual mechanical principles underlying its structure is exceedingly scant. Descriptions of this aspect have usually been limited to brief generalities on the arrangement of the fibers.

The tilting of a tooth under the influence of extraneous forces in function has probably been the most controversial aspect of the mechanics of the membrane, but even this subject is still confused. Oppenheim[19] in 1910 found from experiments on the deciduous teeth of baboons that the application of an orthodontic tilting force, by means of an arch and ligatures, produced a rotation around the apex. Johnson, Appleton and Rittershofer[15] (1926) concluded that the center of rotation lay somewhere between the apex and midroot. Gottlieb and Orban[12] (1931), working with the carnassial teeth of dogs modified by artificial crowns with inclined occlusal surfaces, also found that the apex moved in a direction opposite to the movement of the crown. Fish,[11] from a simple mechanical approach based essentially on the area of attachment, concluded that the center of rotation should lie somewhere between the alveolar crest and midroot. The alveolar crest itself has also been proposed as an axis, and undoubtedly it is one when the applied force is strong enough to bring the tooth into contact with it. These diverging views might cast doubt on the validity of the several conclusions, but with the exception of the work of Fish the differences are in all probability due to differences in the method of approach. As will be shown later in this paper, the axis of rotation is not a fixed point; its location changes with every change in the forces or in the supporting tissues.

The mechanics of the teeth and jaws as a unit have been analyzed by Maxwell,[17] and Fish[11] has discussed some of the principles of force analysis and their application to the teeth. Adler[1] has investigated the effects of leverage in dental bridges, but through a confusion of moments and linear forces he has arrived at conclusions which are the exact reverse of actual conditions. Boyle[4] suggests an hydraulic shock absorber effect of blood vessels on the pressure side of the membrane. This idea is good, and together with that of the resistance of vessels squeezed between fibers on the tension side (Orban[20]) will bear further exploration. Boyle also states that the tooth is part of an Archimedian spiral, acting as a spring to absorb shocks, but this is based on two misinterpretations of work by Thompson[29] and is of doubtful validity.

Synge,[24] Dyment[10] and Hay,[13] all working on the basis of original work by Synge, have developed a mathematic-physical theory to explain the functioning of the periodontal membrane. They have arrived at some interesting conclusions, but their present applicability is limited by the original assumptions made for the sake of mathematical expediency. Some of these assumptions, especially that of incompressibility, do not closely fit conditions in the periodontal membrane though they do influence the results considerably. Later work has brought some refinements, giving promise of possible new findings which might materially increase the value of the whole.

The gross structural pattern of the skull and masticatory apparatus has been thoroughly probed by many investigators, including Brodie,[5] Downs,[8] Kloehn[16] and Seward,[22] so that a comprehensive picture of the distribution of masticatory stresses over the teeth, jaws and skull is now available.

PART I

The Periodontal Membrane in Function as a Unit

The teeth of the higher animals, including man, are maintained in their sockets by a fibrous suspending mechanism, the periodontal membrane. The tasks which this membrane is called upon to perform are varied and exacting. It must resist all of the sudden shocks, sometimes of considerable magnitude, to which it is subjected in every-day chewing. It must endure the long-continued mastication of the gum chewer and the sharp shocks imposed on it by the nutcracker. In addition it is often called upon to support the added loads of orthodontic appliances, bridges, and dentures. The fibers of this membrane support the tooth in its socket in a manner very similar to that found in a suspension bridge or in a hammock, microscopic in size and multiplied in number thousands of times (Fig. 1).

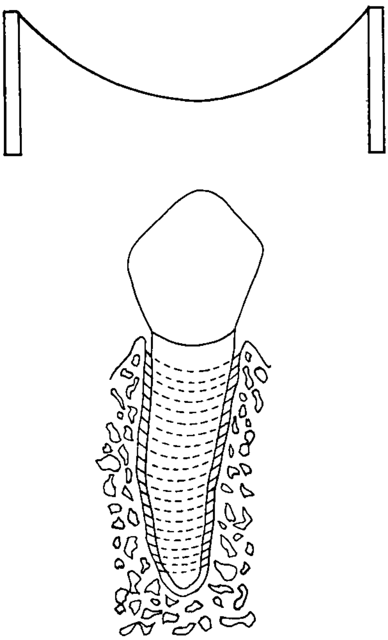

Fig. 1.—The suspension principle of the periodontal membrane.

When a tooth is subjected to a force parallel to its long axis, such as a direct occlusal force (these forces will be referred to hereafter as axial forces), all of the oblique supporting fibers are tensed. As a result the load is distributed equally among these fibers. If the tooth is subjected to a non-axial force, i.e. one with a mesial, distal, labial, or lingual component, the tooth is tipped and the load is no longer evenly distributed among the fibers. What actually takes place in such a case has been the subject of much controversy, but it is now generally agreed that such non-axial forces produced a rotation around an axis located somewhere apical of midroot. This rotation is brought about through a simultaneous stretching of the membrane near the alveolar crest on the side from which the force is applied and near the apex on the opposite side.

This axis of rotation, with the strong evidence which has been advanced to support its existence, has attracted a disproportionately large amount of attention, to the almost complete exclusion of everything else. Actually, a considerable number of its attributes have devolved upon it merely through speaking of it as a fulcrum instead of as an axis, thus inadvertently ascribing to it the additional properties of a fulcrum.

Essentially, a fulcrum is the center of support of a lever, a concrete entity lying at the junction of the effort arm and resistance arm. An axis, on the other hand, is any straight line about which rotation can or does take place. The confusion of the two arises from the fact that in common experience fulcra are usually concurrently axes of rotation, as in the teeter-totter, pulley, and other simple devices; but in the tooth an unusual exception obtains.

Properties of Levers

Before going further with the situation as it exists in the tooth a review of some of the basic properties of the lever as a simple machine may prove helpful.

A lever consists of a rod, such as a teeter-totter or pump handle, supported by a fulcrum, and serving to apply a force at some point along its length when a force is applied at some other point. In this manner it serves to change a forct in direction or magnitude, or both. For the purpose of determining the actual forces involved in a particular case two theoretical arms are introduced. These arms are perpendicular lines from the fulcrum to the line of the applied force and to the line of resistance, and are known as effort and resistance arms respectively. The forces can then be found by means of the following formula:

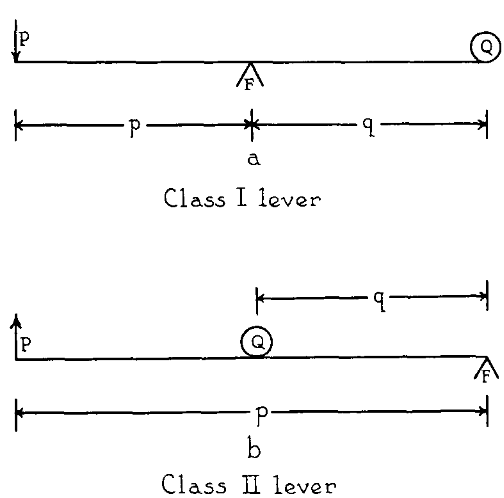

Fig. 2.—(a) Class I lever. (b) Class II lever.

where P = force on effort arm
Q = force on resistance arm
p = length of effort arm
q = length of resistance arm

then $\frac{Q}{P} = \frac{p}{q}$

Levers are usually classified into three general groups, according to the relative positions of the fulcrum and the points of application of effort and resistance. The two classes which apply directly to the problem at hand are known as class I (Fig. 2a), with the fulcrum between effort and resistance, and class II (Fig. 2b) with the force at one end, fulcrum at the other end, and resistance somewhere between.

Lever Principles Applied to the Tilting Tooth Problem

On the basis of the above principles it is now possible to examine

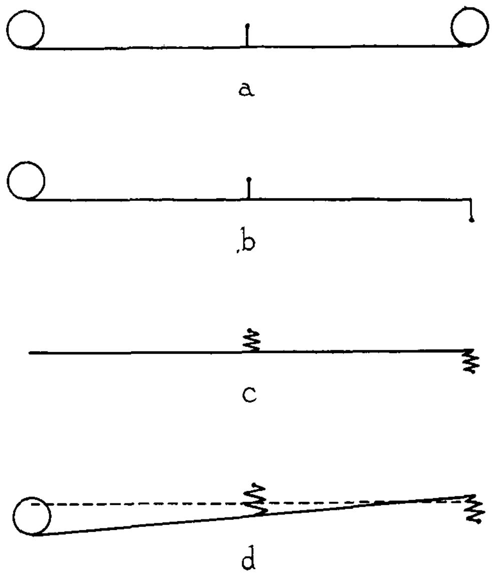

Fig. 3.

the lever system found in a tooth subjected to a force at right angles to its long axis.

In Fig. 3a the rod is supported at the center, with a twenty-five pound weight at each end. It is in a state of stable equilibrium, with all forces balanced. With the support at B as a fulcrum this rod is a first class lever, the weight at A representing the effort and the weight at C the resistance, or vice versa. The pull at B is fifty pounds (neglecting the weight of the bar), which is obvious in this case because of the familiar properties of gravity and weight, but it can also be explained on the basis of lever principles. The usual concept of a lever is a system in which there is a definite fulcrum with clearly defined force and resistance, but when a condition of stable equilibrium exists any one of the points can be considered as the fulcrum and the other two as force and resistance respectively without altering the forces involved. In the case at hand, if C be taken as fulcrum, A as force, and B as resistance, a second class lever results. Then using the formula for the forces on a lever it is found that:

where $p = AC = 2CB$
$q = CB$
$P = 25$ lb.
$Q =$ force at B

and $$\frac{Q}{P} = \frac{p}{q}$$

then $$\frac{Q}{25} = \frac{2CB}{CB}$$

and $Q = 50$ lb., the pull at B.

Fig. 3b shows the same lever with point C immobilized and the weight removed. In this case the equilibrium is maintanied and the force at each of the three points remains unchanged.

The lever in Fig. 3b is actually the same as is found in the tooth, but to complete the picture one more change is necessary. Instead of fixing points B and C with solid bonds, extensible springs of equal strength are subtituted

(Fig. 3c). Twenty-five pounds is again applied at A (Fig. 3d). The forces are still the same. The rod is again in a state of stable equilibrium. The fulcra are still at the same points. The only change from Fig. 3b is that the springs have stretched, so that the rod has *rotated around a point between B and C.* The force at B being twice that at C, the spring at B is extended twice as far as that at C, placing the axis exactly ⅔ of the distance from B to C (point D). Of course as the rod rotates the lever arms will be changed slightly, but this is of no importance for purposes of this illustration.

The axis D has entered the picture without bringing any change in the nature of the lever or the forces on it. It is a *product* of the machine, not a part of the machine itself.

System of Analysis to be Applied to Tooth Sections

Although the simple lever serves well to illustrate the principle involved in the tilting of a tooth and the naure of he axis of rotation, there are two differences in the actual tooth which make modifications necessary before a detailed analysis of forces can be made.

First, the labial and lingual supports of a tooth subjected to non-axial stress are not attached at two discrete points as were the springs on the lever. The supporting fibers are attached over the entire area from approximately midroot to the alveolar crest and from midroot to the apex on the respective sides. It is therefore necessary to determine a center of resistance on each side which can be considered mechanically as the point of attachment for all the resisting fibers on that side. In a tilting tooth the possible effectiveness of the fibers increases in a linear manner from zero at the neutral midroot section to maxima at the alveolar crest and near the apex. Thus the centers of resistance would lie $\sqrt{1/2}$ or .706 of the distance from the neutral point near midroot to the crest and apex. This is the figure which would apply if all the stressed fibers were tensed equally, but due to the fact that the tapering thickness of the membrane is not extreme enough to allow full tension to fall on the fibers near midroot it is obvious that these fibers cannot share the stress fully. As a result the center is shifted farther from midroot. For this reason the centers of resistance in the following schematic examples will be taken at points approximately ⅛ the length of the functional root from the crest and the apex.

The other necessary change is in the method of analysis itself. The simple lever is applicable for determining forces on all three cardinal points of a lever only when they lie on a straight line. In all other cases the force on the middle point is altered by the angulation and a different approach is necessary to evaluate these effects. The approach to be used here makes use of what is known as the "Free Body Principle." According to this principle a body is in equilibrium (a tooth is in momentary equilibrium when a force is applied) when the following three conditions are fulfilled:

1. The algebraic sum of all vertical forces is zero.
2. The Algebraic sum of all moments of rotation about any axis is zero.
3. The algebraic sum of all horizontal forces is zero.

In Figs. 4-7 the long axis of the tooth, indicated by a black line, is taken as the vertical axis. All forces on the tooth are reduced to vertical and horizontal components by simple vector diagrams. In studying the vectors it must be remembered that they represent the forces acting *on* the tooth, hence those representing the pull of the periodontal fibers act in a direction opposite to that in which the tooth is moved.

The center of resistance lying nearest the alveolar crest is the axis about which all moments of rotation are taken. A moment is the product of a force multiplied by the perpendicular distance from the line of its action to the axis of rotation.

In the original diagrams the linear units used for vectors and moment arms were ½ millimeter. The size of these units is of only momentary significance however as they cancel out in the final result.

In considerations such as will be made here concerning the forces on teeth the results are of significance primarily on a comparative basis. Definite figures in pounds or grams would of necessity be highly arbitrary and of limited application, and could too easily give a false impression of the nature of the conclusions. For this reason the applied force in each of the following examples is taken as 100, without specifying concrete units. Results may then be easily compared on a percentage basis and, if desired, the effects for a specific force may still be determined by substitution.

Analyses of Typical Tooth Sections

The first case (Fig. 4) is a mesio-distal view of upper and lower central incisors in average incising relation. The analysis of the forces on the lower incisor will be covered in detail as an illustration of the method. In the other cases which follow, the same method of analysis will be used but only the results will be discussed.

Detailed Analysis of Forces on Lower Incision: In Fig. 4 the forces on the two teeth are equal and opposite, perpendicular to the tangent at the point of contact. On the lower incisor the force of 100 is resolved by vector diagram into a vertical component of 93 and a horizontal component of 36. Assuming that the vertical load is borne equally by the membrane on each side of the tooth, vertical vectors of 46.5 are drawn at each center of support in an upward direction. This balances the applied downward load, giving equal vectors in each direction and satisfying requirement number one of the free body principle. The actual distribution of the vertical force between gingival and apical fiber groups has not yet been accurately determined. In all likelihood the greater part is borne by the gingival fibers, which carry a greater part of the total load, but as any allowance in this direction would only serve to increase the difference between gingival and apical stresses it was considered better to us an estimate which might minimize rather than exaggerate conclusions.

The next step is to determine the moments about the axis, which was chosen at the gingival center of support. The applied force of 100 produces a clockwise moment of 4800. The moments of the two components of this force could be determined separately, but the result would be the same and the diagram more complicated. The upward force of 46.5 at the apical center, acting on a moment arm 36 units long, produces a counter-clockwise moment of 1674. This leaves a counter-clockwise deficiency of 3126 which

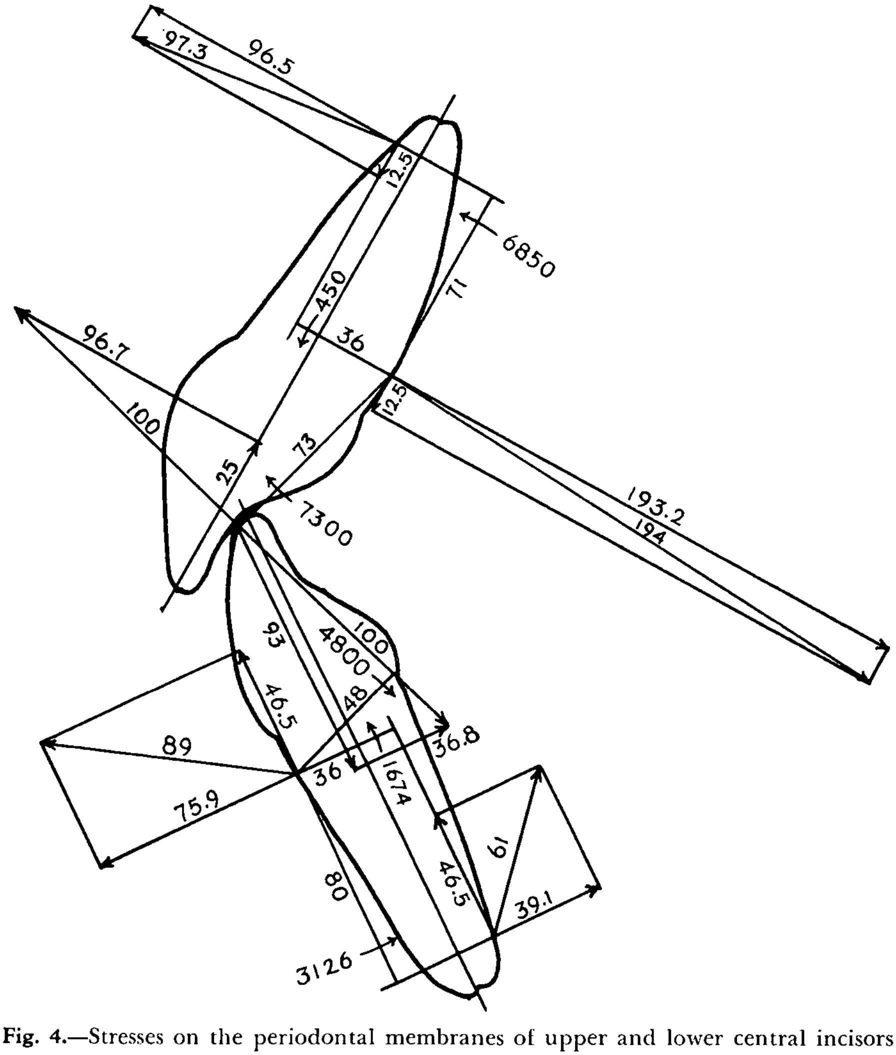

Fig. 4.—Stresses on the periodontal membranes of upper and lower central incisors in an average incising relation.

must be supplied by the horizontal component at the apical center. This component of force, acting on a moment arm 80 units long, must therefore be 3126/80 or 39.1. When this horizontal component is drawn at the apical center that vector diagram can be completed and the resultant force on the membrane determined. In this case the resultant is found to be 61. This resultant vector indicates both the intensity and direction of the strain on the apical fibers.

The last condition for equilibrium, that the algebraic sum of horizontal forces equal zero, now makes possible the rapid completion of the picture. The horizontal components of both the applied force and the apical resistance of the membrane are directed to the right. Their sum of 75.9 must be balanced by the horizontal component of the gingival resistance. Construction of this component of 75.9 directed to the left at the gingival center supplies the vector necessary for completion of the gingival vector diagram and determination of the resultant. The final result shows a stress on the gingival tension side of 89 and an apical stress of 61, a ratio of about 1.5 to 1.

Upper Incisor: The upper incisor, where the angle of application of the force to the long axis is greater than on the lower, shows a ratio of gingival stress to apical stress of 2 to 1. This ratio changes in the same sense as the angle of the force to the long axis of the tooth is changed.

Effect of Changing the Point of Application of the Force: Fig. 5 shows a purely horizontal force applied at two different points on a tooth. In Fig. 5a it is applied at the cervix, producing a gingival stress of 117 and apical stress of 17. In Fig. 5b it is applied at the incisal edge and the stresses are

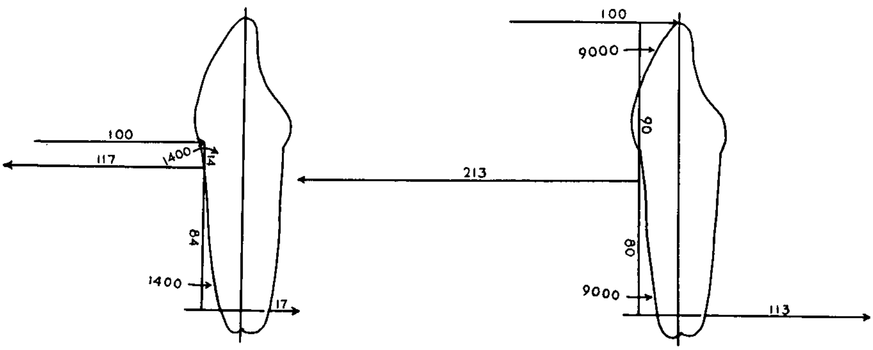

Fig. 5.—Influence of the point of application of a horizontal force on the resulting stresses in the membrane.

increased to 213 and 113 respectively. From this it can be seen that moving the point of application incisally brings about an increase in the stresses on the membrane and a simultaneous decrease in the ratio between gingival and apical stress.

The Axis of Rotation: As the ratio between gingival and apical stress is an index of the comparative stretching of the membrane which might be expected at these points, it must also give an indication of the location of the axis of rotation of the tooth. Accordingly, shifting the point of application of force to the tooth will bring about a shift in the location of the axis of rotation.

The highest point incisally which this axis can theoretically attain lies midway between the two centers of support. This point is reached when the stresses on each side are equal, a condition found when the force is applied either at an infinite distance incisally or in a direction parallel to the long axis of the tooth. As the force is applied more apically, or the angle with the long axis increased, the axis of rotation retreats in an apical direction until it reaches infinity when the force is applied at right angles to the long axis at the gingival center of support. If the force is applied even more apically the axis again moves incisally as the tooth rotates in the opposite direction.

Moving the point of application of force apically brings into action more fibers toward the apical end of the tooth, so that the gingival center of resistance also shifts apically. When the axis of rotation is at infinity all fibers on the side where the force is applied are under tension and the center of resistance is somewhere near midroot.

This brings about another interesting condition. As the point of application of the force is moved apically and the stress on the membrane is decreased, the number of fibers actually bearing this force is increased, so

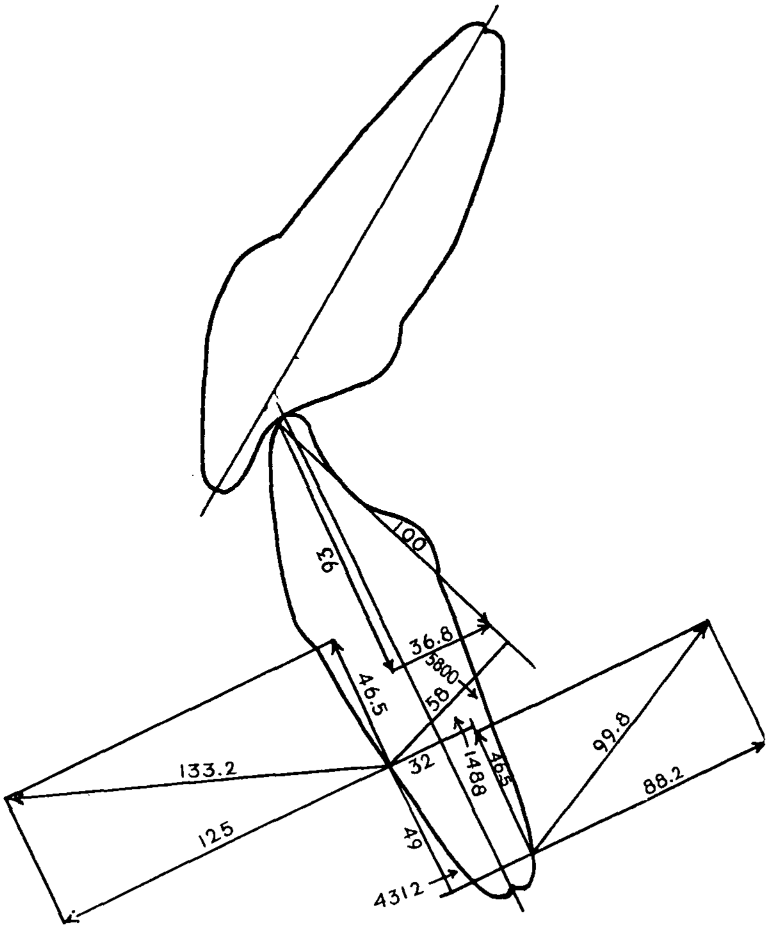

Fig. 6.—Result of loss of periodontal attachment (recession). Compare with Fig. 4.

that the resistance of the membrane is at its peak when the force is applied at the center of resistance and the maximum number of fibers are resisting the minimum of stress. Conversely, the farther the point of application is moved incisally the greater is the force which must be borne by the diminishing number of fibers in action.

On the other hand, the situation for the apical fibers is exactly the reverse. As the stress is increased the number of fibers in action is also increased, though not necessarily in the same proportion.

Effects of Periodontal Recession: Fig. 6 shows the same teeth in the same relation as in Fig. 4, but in this case the periodontal attachment has receded until the labial center of resistance is at the point shown. The resultant forces are now 133.2 at the gingival and 99.8 at the apical center, as compared with 89 and 61 in the case with normal periodontal attachment. These figures

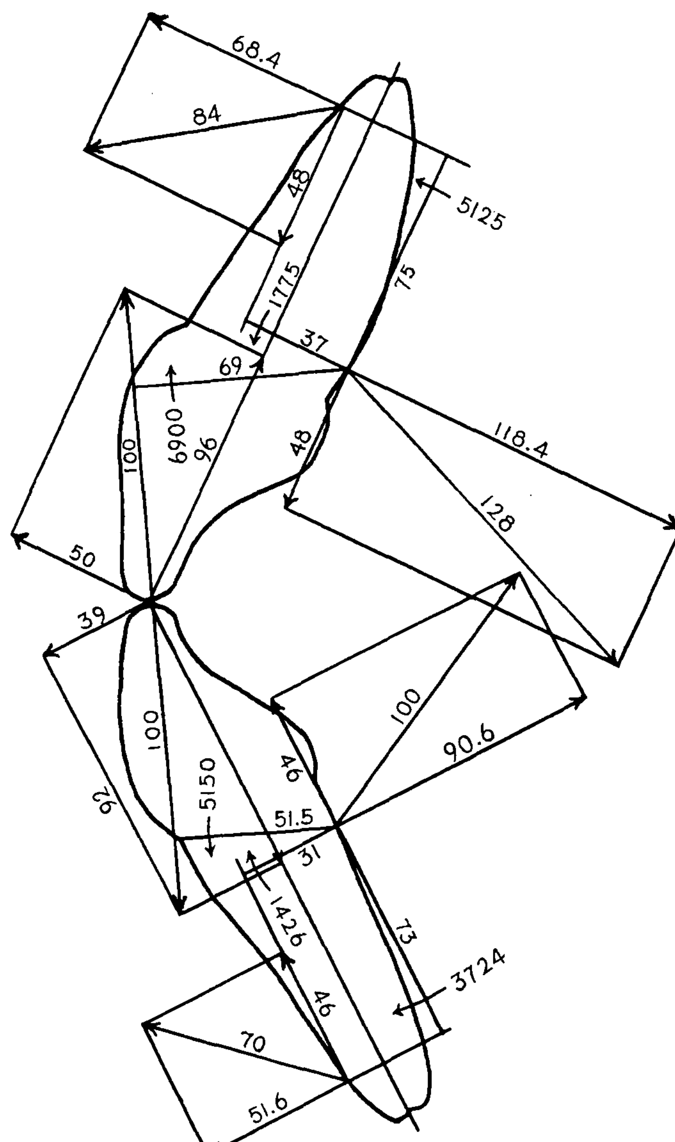

Fig. 7.—Central incisors in edge-to-edge relation. Compare with Fig. 4.

show the increased stress which must be borne by the reduced number of remaining fibers, so that the actual stress per fiber is increased simultaneously by two factors. The situation is the same as that brought about by moving the point of application of the force incisally.

The insidious nature of resorption of the alveolar crest, particularly in cases of tilted teeth, is now evident. Stress increases rapidly, especially on the fibers nearest the alveolar crest which will be the next to go. The fundamental importance of maintaining teeth at their proper axial inclination and of keeping the periodontal attachment at the highest possible level is apparent.

End-to-end Bite of Incisors: Fig. 7 shows upper and lower central incisors in end-to-end relation. The chief difference from Fig. 4 is the reversal of the tilting effect on the lower tooth. This serves to illustrate the extreme variability of force conditions and to emphasize the fact that no single diagram can show all conditions even for a single tooth. Each case is a distinct problem in itself and must be explored in the light of the prevailing circumstances.*

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* The second part of this presentation will be published in THE ANGLE ORTHODONTIST 15: July-October 1945.