PIEZOELECTRIC THEORIES OF BONE RESPONSE TO ORTHODONTIC FORCE.

When bone responds to orthodontic force by cellular activity, a system as yet undefined, operates to convey the force as a cellular stimulant and to regulate precisely the resulting activity of the cells, whether it be osteoclastic or osteoblastic in effect. This system could be likened to a transducer mechanism.

Several investigators have examined the subject of bone response to stress generally and a number of different hypotheses have been given. The findings of these investigators have a direct bearing on the subject of the response of bone to orthodontic force.

In 1957 Fukada and Yasuda investigated the response of bone to applied force and were the first to claim that the response was due to a piezoelectric effect of the collagen content of bone (Bassett 1965 [4], Shamos 1965 [112]).

Bassett and his colleagues 1962 to 1965 [4, 7, 13], also proposed a piezoelectric theory of bone response to stress and conducted experiments in attempts to prove this theory.

About the same time Shamos, Lavine and Shamos 1963-1967 [112, 115, 116], also offered the theory of piezoelectricity to explain the bone stimulating effect and conducted experiments, but differed from Bassett and his colleagues in their conclusions.

A short review of piezoelectricity and piezoelectric effects of crystalline and non-crystalline di-electrics is given in Appendix I.

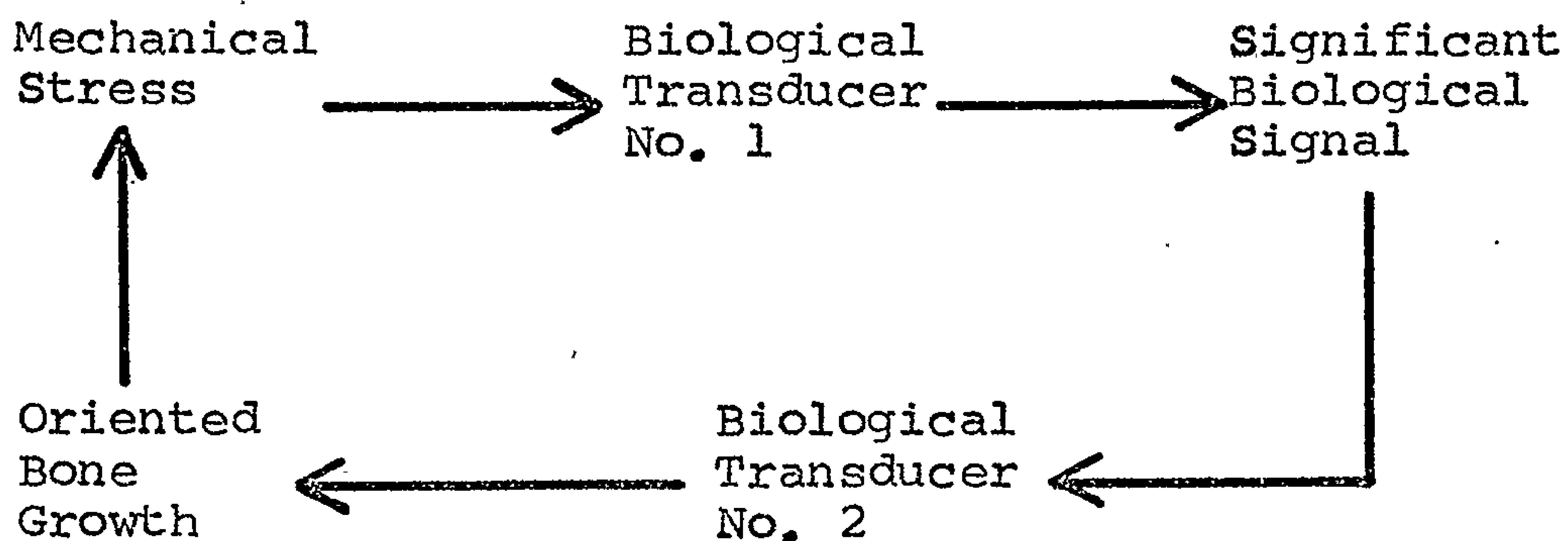
Firstly, the hypotheses and experiments of Bassett and Becker and their co-workers will be discussed.

In 1962 Bassett and Becker [7] experimented to find whether mechanical deformation of bone could produce measureable d-c potentials in bone. They applied stress to feline fibulae in the hydrated state. The bone was bent and electrodes, so placed that they registered the potential difference between the concave and convex surfaces, showed a negative charge on the concave surface and a positive charge on the convex surface. The charges were proportional to the stresses and the charge was lost when the bone was returned to the normal shape. The charge reversed when the direction of bending was reversed but showed equal magnitude for equal deformation. The potentials registered were not related to cell viability as other tests were made on frozen and thawed and on air-dried samples and definite potentials were registered. These potentials, however, were 25% less than those recorded from the fresh sample. Also tested were strips of wood, and tendon from a cat. No potential was detected in these materials, or in decalcified bone. This has significance when the work of Shamos is discussed. An

attempt was made to measure the potential in bone from which the organic matrix had been removed but the bone was too fragile and it collapsed before a reading was registered.

Bassett and Becker concluded from these experiments that a negative potential develops in a case of compression. They noted that the initial potential was similar to the reaction from a deformed quartz piezoelectric crystal, but that there was a steady state potential indicating a direct current flow which was unlike the classic, simple piezoelectric effect. They stated that these experiments had not shown that bone cells will respond to alterations in electric charge.

Becker, et al. 1964 [13] linked their theory to Wolff's Law and proposed a control system consisting of a simple closed loop feed back in which the response was fed back to the original signal and cancelled it. They pointed out that bone is quasi-crystalline in nature and on this account can be subjected to solid state physical methods of experimentation. Their system was set out as follows overleaf.



Bassett 1965 [6] referred to the above circular system as a negative feed back system due to the original signal being dampened, not enhanced.

Becker, et al. 1964 [13] next conducted experiments to measure stress-generated potentials and also to demonstrate solid state characteristics of conductivity, photoconduction and fluorescence. Samples of fresh bone were used to measure the stress potentials.

They found the results confirmed their previous observations that the compression side of the stressed bone registered a negative charge, that the current decayed somewhat after an initial surge, and that opposite directional flow occurred when the stress was released.

Becker, et al. 1964 [13] stated again that the current produced was different from that produced by classic piezoelectric crystals; also that semi-conducting substances having positive-negative (P.N.) junctions have

non-classic piezoelectric properties. They then stated that bone is a two component system, having crystals of apatite and collagen precisely orientated. Therefore, they presumed that this unit may form a P.N. junction responding to mechanical stress.

They claimed that their conductivity tests of whole bone in the fresh state, dried or dehydrated, and of bone collagen also indicated that bone has definite semi-conductor properties. Experimental confirmation was also given that the stress-produced currents were temperature dependent, which was claimed as further confirmation of semi-conduction.

Experiments also demonstrated the photo-conductivity of isolated collagen, bone mineral and whole bone. This again pointed to bone being a semi-conductor.

Becker, et al 1964 [14] concluded from these results that both collagen and apatite are semi-conductors and that the stress-generated electrical phenomena are related to this property.

Becker and Brown [16] in 1965 conducted further tests of photo-conductivity on bone with similar results to those obtained by Becker, et al. [13]. The conclusion was that the results supported the hypothesis that the apatite - collagen complex has the properties of a semi-conducting P.N. junction diode.

Becker, et al. 1964 [13] when testing whole bone for fluorescent effects to support their theory of semi-conduction were unable to obtain results which justified forming any opinion.

However, in 1965 Bachman and Ellis [2] experimented with fluorescence of bone. The apatite was separated from the collagen but the crystallites were left in the collagen bundles. Bachman and Ellis found the collagen, with included apatite, to be the main source of fluorescence in bone. When considered with the hypothesis of Becker, et al. [13] concerning semi-conduction characteristics, this result would support the evidence that bone is a semi-conductor.

Continuing their experiments, Becker, et al. [13] measured the electrical characteristics of the apatite - collagen P.N. junction using samples of anorganic bone and demineralized bone. They found that all apatite samples were P. type carriers and all collagen samples were N. type. They then related the stress-generated electrical phenomena directly to this multiple P.N. junction [15].

Thus a mechanism was found to satisfy the requirement of the first transducer and an appropriate signal was generated therefrom.

Becker and colleagues next sought to find a mechanism

to complete the requirements of Transducer No. 2.

They stated (1964 [15]) that collagen fibrils, formed in the organic matrix of bone, control the initiation and orientation of hydroxyapatite crystals.

Termine 1972 [140] also wrote of the ability of collagen fibres to influence mineral formation and the orientation of apatite crystallites. He concluded from chemical evidence and electron microscopy that the mineral formed directly on or within the collagen fibres.

Becker and his colleagues showed by experiment that soluble collagen molecules could be orientated into parallel structures in a very weak electric field of 0.2 to 2 microamperes in from 5 to 50 minutes. The current approximated that generated in bone under stress. Becker and his colleagues concluded from this result that collagen laid down in the organic matrix of bone could be influenced as to direction by the stress-generated electric currents and could perhaps explain the orderly structure of lamellae and osteons in bone. This experiment established the basis for their concept of Biological Transducer No. 2 giving oriented bone growth. They suggested that further study be conducted on the effects of electric currents on cells.

To further this study Bassett, et al. 1964 [8] tested the effects of electric currents on living bone of dogs.

Battery packs were placed under the skin with electrodes embedded in the femur. Nominal currents of 1 µA., 10 µA. and 100 µA. were used, but actual currents of 0.7 - 3 µA. were delivered. The result was that relatively large deposits of new bone were formed at the cathodes of the 10 µA. and 100 µA. packs. There were large numbers of osteoblasts seen in the area of new bone. However, no increase was noted in the number of osteoclasts around the anode. Their distribution was uniform throughout the areas of reaction.

To explain the absence of observed osteoclasts at the anode, Bassett 1965 [4] hypothesises that, as electrical negativity connotes an accumulation of electrons, and positivity, the absence of electrons, then osteoclasis may occur in the absence of electric currents but not when a current is flowing in the area.

He drew attention to various states which lead to osteoporosis, i.e. osteoclastic activity, such as the weightlessness of astronauts, the bed-ridden, and the case of loss of function of a part of the skeletal system. All these states have a lack of stress as the apparent initiator of the associated osteoporosis. The inactivity or lack of stress leads to lack of electric current flow according to Bassett's piezoelectric theory and may thus favour osteoclasis.

He discounts the idea that electrophoretic action may have attracted an undue number of osteoblasts to the cathode. If this were so he would have expected a gradient effect which was not present. He theorised that the result was caused by mitosis. Also, he stated, most cell membranes are negatively charged and move towards the anode in an electrophoretic chamber. Bassett would not accept this result as final proof that bone formation was related to electro-negativity or that bone resorption was likewise related to electro-positivity. However, he was of the opinion that there was a definite link between bone formation and direct electric current flow.

It is to be noted that in most of the foregoing experiments of Bassett and his colleagues, whole bone in the hydrated state was used.

The conclusion reached was that an electric current is generated when bone is stressed, due to its being a piezoelectric substance. Also that the bone collagen and apatite form a semi-conductor junction of the P.N. type. This electric current stimulates the activity of the bone forming cells.

Bassett gave no experimental evidence of osteoclastic activity. He theorised (1965 [5]) on an unreal orthodontic situation to support his contentions concerning osteoclasia. His theoretical orthodontic force of

1 - 2 grams in humans was far too light to be practical.

He stated (1965 [6]) that bone in the body that has lost its living tissue may continue to generate potentials if it is intermittently deformed; thus it may escape destruction by osteoclasts.

Further experiments on the promotion of bone formation by electrical current stimulus.

O'Connor, et al. 1969 [91] also experimented on the promotion of bone growth in living animals, by electrical current stimulus. In general, they confirmed the findings of Bassett, et al. 1964 [8].

They embedded battery packs which delivered between 90 µA. and 100 µA. in the femur of dogs.

After 21 days it was found that nearly all electrodes had new bone growth around them. The electrically active electrodes had bone growth of a similar type to that around the control electrodes. However, the cathode did not always have the most new bone associated with it.

O'Connor, et al., commented that there is a considerable clinical variation in the response of bone to electric current.

Pawluk and Bassett 1970 [97] further experimented with the promotion of osteogenesis by stimulation of bone cells

with an electric current.

They refined their previous technique by using 20 litter-mate beagle dogs of a known age, to eliminate variables in response induced by differences in age and breeds.

They used the femur as the experimental site and produced a series of three defects in the cortical bone, two holes 4 mm. in diameter and one hole 5 mm. in diameter. One 4 mm. hole was left open, the other 4 mm. hole was closed, with a teflon plug and the 5 mm. hole fitted with a teflon ring with an inside diameter of 4 mm.

On the control animals, new bone filled the open holes within 4 weeks. The teflon plug was covered with new bone and the diameter was reduced where it passed through the cortical bone within 70 days. The teflon ring was filled within 4 weeks with fibrous tissue, and fibre bone within 10 weeks.

The teflon ring had the advantage of substantially diminishing the rate of osseous bridging and had a volume appreciably greater than the combined volume of the subsequently inserted electrode and any reactive bone encapsulating this electrode.

In the next stage of the experiment electrodes were placed so that two electrodes of similar polarity bridged the teflon-lined hole and one electrode of opposite

polarity projected through the teflon ring.

This middle electrode was negatively charged and passed a current of 3 - 4 μA. of direct current for 4 weeks, resulting in completely filling the teflon ring with young fibre bone.

These results were not obtained when the electrode was positively charged or inactive.

Pawluk and Bassett stated that electrical stimulation seemed to induce more rapid healing of defects in cortical bone and that the experiment suggests bone resorption can occur at the positive electrode.

The experiments which have been quoted concerning bone cell stimulus by electrical currents, are evidence of the reverse piezoelectric property possessed by bone crystals in respect to the formation of bone. The evidence of the promotion of osteoclastic activity by electrical stimulus is not convincing.

Alternative Piezoelectric Theory.

Shamos, et al. [116] in 1963 performed experiments to test their theory of piezoelectricity. Bending and compression forces were applied to bone and a difference in potential was recorded in both situations.

Dried bone was used in these tests and this may give a different result to normal hydrated bone. The theory proposed as a result of the tests was that the electric

charges induced may influence the orientation and deposition of ions or polarizable molecules.

In 1965 Shamos [112] theorized on the piezoelectric effect. He mentioned that in his previous experiments, dry bone was used which may upset the results. He also stated that, contrary to Bassett's findings, he was unable to observe any photo-conductivity or rectifying action in whole bone.

Shamos stated that the piezoelectric effect varied with the angle of application of the force to the collagen axis, being greatest when the angle was 45°. He theorised that cross-linkages between collagen were displaced, causing strains and a micro-electric effect. This was taken to be evidence that the collagen alone was the piezoelectric substance in bone. Also, the strength of the electric field was linear with the stress, and changed polarity on reversal of the stress, i.e. when tension was applied. These properties are characteristic of classical piezoelectricity. Shamos claimed that the piezoelectric effect in whole bone was due to the collagen content. This could be supported by Bachman and Ellis' 1965 [2] finding on fluorescence where the collagen content seemed to be the most active material. Also Bassett was unable to produce any results relating to stress from testing of the mineral phase of bone with the organic phase removed.

Shamos and Lavine 1967 [115] produced evidence to show that the piezoelectric effect is related to the collagen axis in bone, by referring to the X-ray diffraction pattern being displaced from the bone axis of the human femur by 10°. This is the angle of displacement of the collagen fibres which are vertical to resist stress when in the standing position, whereas the femur itself is not vertical. The reference to dried tissue is made again with the inference that the results from fresh tissue could be different.

As one of the characteristics of piezoelectricity is the reversibility of its effects, some examples are presented supporting this reversed piezoelectric theory as applied to bone.

In 1972 Lavine, et al. [64] described the electrical stimulation of bone growth by means of a "current-sensitive" method. The patient had a pseudo-arthrosis which was healed by graft and then subsequently fractured, followed by inability to heal the defect. This failure to unite had persisted for more than two years.

An electric current was passed between platinum electrodes inserted in the bone on either side of the fracture. Healing occurred in 4 months. Lavine, et al. claimed that this was an example of osteogenic stimulation by electric current due to piezoelectric properties

of bone.

Becker [11], in 1972, reported further confirmation that electric currents can stimulate bone growth. He succeeded in inducing partial limb regeneration, including bone substance, in a number of rats after amputation and implantation of wires carrying an electric current, at the site of amputation.

Shamos and Spruch 1966 [117] conducted experiments related to the effect of light on bone relative to Becker and Brown's 1965 [16] findings. Shamos and Spruch concluded that the effect was simply one of heating in the bone.

Bazhenov [10] in 1961 reported on the piezoelectric properties of wood. These findings point to a flaw in Bassett and Becker's [7] experimental technique in 1962 when the latter were unable to obtain a piezoelectric effect from wood.

Shamos and Lavine [113] in 1964 conducted experiments on several materials including bone collagen and cortical bone relative to the temperature dependence of stress-produced currents in these materials. Their findings were that there was no evidence of semi-conduction effects except at very high temperatures. Insulators also show this effect at these same high temperatures. These findings are at variance with those of Becker, et al. [13].

Shamos and Lavine 1965 [114] stated that photo-induced conductivity and fluorescence are found in insulators. These properties are not then proof of semi-conduction in a material as claimed by Becker and Bachman and their co-workers 1965 [2, 16].

In this same article Shamos and Lavine 1965 [114] point out that Becker and Bachman 1965 [12] have confused the release of stress with application of tension when reporting on alternating current effect in bone when stress is removed. Shamos and Lavine 1964 [113] had discussed this matter previously and pointed out that the reverse electric pulse on removal of stress is due to the release of charge from the capacitance of the system when the polarization is released in the stressed bone.

Shamos and Lavine 1964 [113] maintained that a semi-conductor rectifier theory is unnecessarily complex to account for the electric effects observed when bone is stressed. They claimed that a classic piezoelectric effect is produced in stressed bone.

Orthodontic and Orthopedic Bone Response - Apparent Inconsistencies.

Epker and Frost [37] in 1965 challenged the current thinking in regard to the response of bone to force, and examined some apparent inconsistencies between orthodontic and orthopedic bone response.

They pointed out that orthodontic thinking was that compression forces cause bone resorption, and that orthopedic thought was that compression forces cause bone deposition. Instances of apparent contradictions were cited, i.e. (i) end loading on a bent bone causes deposition on the concave side and eventual straightening, (ii) a tooth subjected to a force will move to the side of the socket farthest from the applied force and resorption of this side will then take place, (iii) the compression of the underside of the calcaneus bone in the heel which takes place in walking causes neither resorption or deposition of bone, (iv) the teeth are compressed into the sockets during eating but do not move down into the bone as age advances. In all four examples bone is compressed but reacts in different ways.

Epker and Frost theorised that this paradox showed that the common factor of compression could not cause these different results. Further, that there must be some other factor present which could cause the pattern of resorption and deposition.

To find an explanation, they conducted a biomechanical analyses using diagrams and physical analogues.

As a preliminary to their investigations, Epker and Frost considered the result of applying a force to a tooth or directly to bone, i.e. that stress is generated in the bone with resultant strains.

But, further to this consideration, the direction of the load, the strain, and the stress, in relation to the bone surface, was taken into account, together with the change in the surface curvature as the external force was applied to the bone. This latter observation was the crux of Epker and Frost's theory.

Two aspects of bone loading were examined. The first was the case of the side loaded tooth socket, and the second was the bent long bone.

In the case of the tooth socket (see Figs. 1 and 2), Epker and Frost showed that on the compression side the bone of the socket wall was stretched and became slightly thinner and the side facing the force became less concave. On the tension side, the socket wall got slightly thicker and the curvature of the side facing the tension force became more concave. The relation of the trabeculae was shown and the increase or decrease in the angulation of the trabeculae to the socket wall was related to increase or decrease in curvature of the surface of the trabecular plates.

Fig. 1 A.

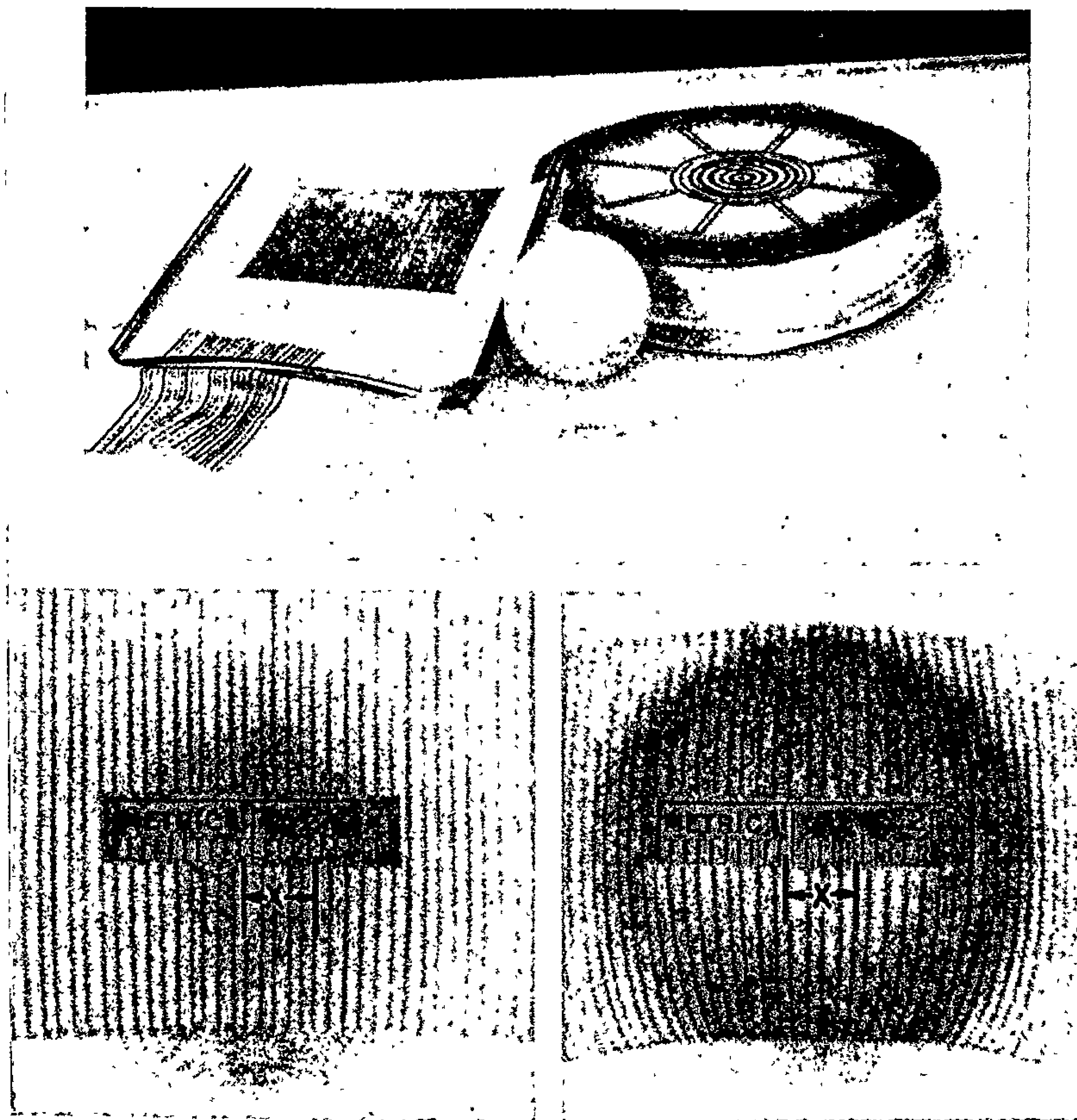


Fig. 1 B. Fig. 1 C.

Fig. 1. - (A), The ping-pong ball and rubber analogues are shown that were used in Figs. 1 B, 1 C, 2 A and 2 B. The lines were drawn on the rubber dam with a ballpoint pen. (B), The rubber dam is resting lightly on top of the ping-pong ball. The ruler is a short segment of a millimeter scale resting on the rubber dam. (C), The dam is now stretched over the ping-pong ball by pushing it down, showing an increase in the separation between the inked lines on the rubber. This is tension strain parallel to the surface of the dam. This is a physical analogue that shows that ahead of the side-thrusted tooth, the socket wall tends to enlarge in circumference.

(After Epker and Frost 1965 [37]).

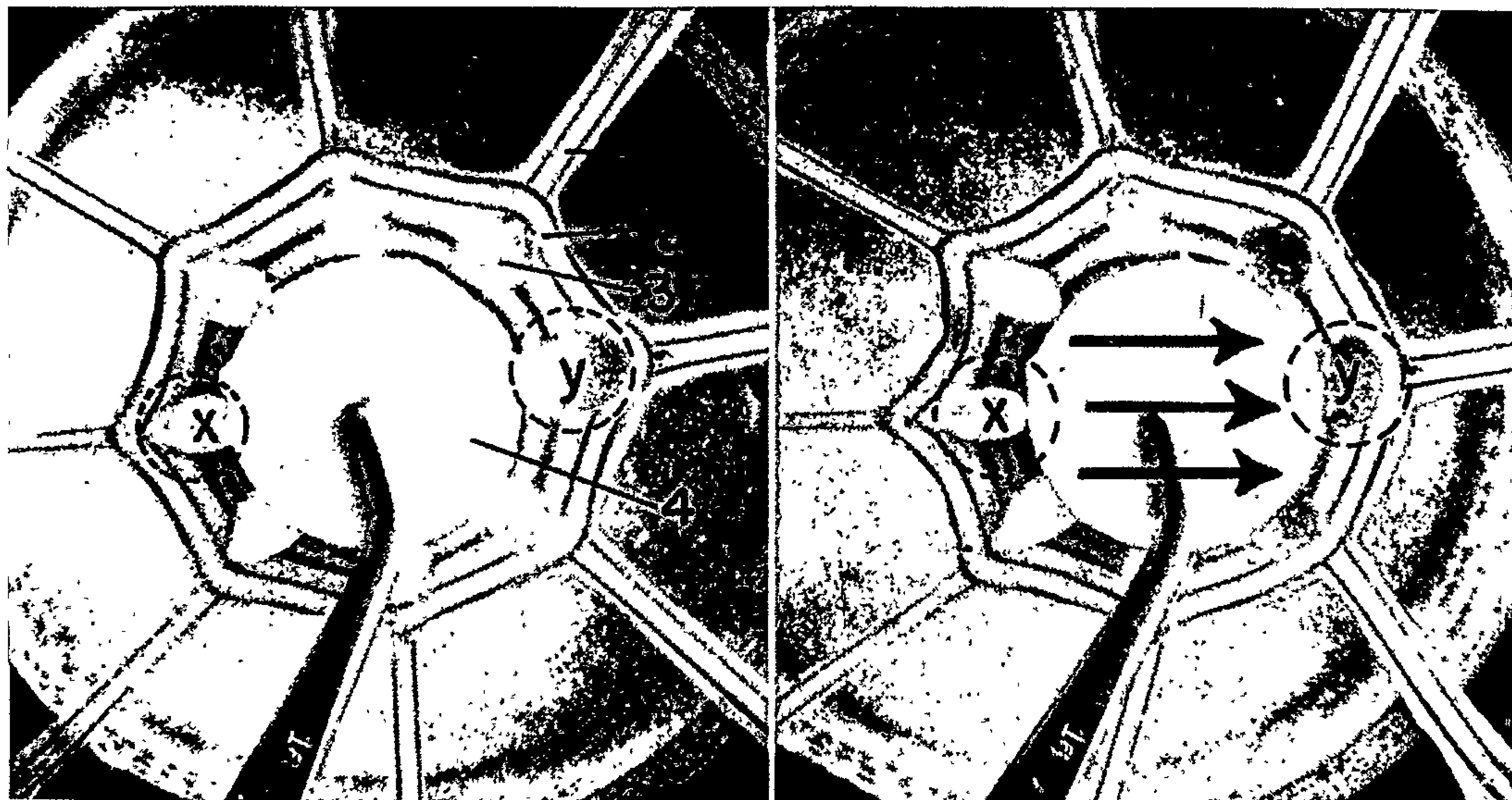


Fig. 2 A. Fig. 2 B.

Fig. 2. - (A), Looking down at an analogue of a cross-section of a tooth in its socket. The central white disc is the tooth. The outermost radial strips of rubber are the trabeculae imbedding the socket in the mandible. The intact ring at (X) and (Y) is the socket wall. The short, thick strips between the wall and tooth represent the periodontal membrane and ligament, a most important feature to include. The forceps provide a way of side-loading the analogue. (B), A right side load has been introduced. Note that the socket has become somewhat elliptical, but in an odd way. There is an increase in socket concavity on the left (tension-loaded side) and a decrease on the right (compression-loaded side). There is little change in curvature at the top and bottom. The trabeculae outside the socket affect its manner of deformation significantly. Those on the right in effect are pushing toward the left. Those on the left are pulling toward the left. The changes in the corner angles between the trabeculae and the outer wall of the socket are such that drift toward the right should occur in each instance if the surface curvature hypothesis in this paper is correct. This is the actual nature of the drift in real sockets. If the trabeculae and periodontal ligament were not modelled, the physical behaviour of the surfaces would be quite different from that shown here.

(After Epker and Frost 1965 [37]).

When the bent long bone was considered, there were four surfaces involved, the inner and outer tension sides, and inner and outer compression sides. The resorption and deposition patterns were not consistent with the stresses, i.e. the outer tension side was resorbed and inner tension side had bone deposited on it. On the compression side, the outer plate had deposition of bone and the inner plate had resorption.

The changes in the surface curvature caused by the load on the bone did correlate with the pattern of resorption and deposition of bone. Increased concavity was associated with bone deposition and decreased concavity was associated with bone resorption.

This theory also applied to the loaded bone of the tooth socket. The socket wall on the compressed side became less concave and was resorbed, and on the tension side where the bone became more concave there was deposition of bone.

They then concluded that their findings correlated with Bassett's results from his experiments on stressed bone and his findings of electric potentials existing between the convex and concave sides of these stressed bones.

Epker and Frost gave a hypothesis that when a force is applied to bone the biomechanical property that controls the resorption or deposition of bone is the change in surface curvature as the load is applied. At the bone

surface that becomes less concave, net resorption occurs, and at the surface that becomes more concave net deposition occurs.

Further, they suggested that there was some minimum deformation necessary before there was a large enough electrical signal to initiate the bone cells. Also, they theorised that if the changes in surface curvature did control the resorption and deposition of bone, then it must be a negative feed back system.

Epker and Frost pointed out that their hypothesis did not depend on the effect of loads on bone but on the strain produced by these loads. The main aspect was the deformation produced which was the physical property that controlled the bone response to applied force.

Epker and Frost [38] in 1966 conducted further experiments on human ribs with tetracycline labelling to examine the validity of theories they had formulated concerning the influence of muscle force on the form of bone.

They postulated that (i) the change in the curvature of a bone caused by muscle forces determines its pattern of periosteal surface resorption and formation, (ii) a surface that usually becomes more concave or less convex during flexure is a site of bone formation, (iii) a surface that usually becomes more convex or less concave is the site of bone resorption, (iv) a bone achieves a stable

cross-section, size and shape when the relationship between the physical forces acting on it and its physical properties is such that the changes in curvature tend to be equal and to cancel out on all parts of its periosteal surface when averaged over time. Epker and Frost stated that this was a muscle-force / bone-mass system and was also a simple negative feed back system. The influence of the masseter muscle and internal pterygoid muscles on the shape of the angle of the mandible and the influence of the temporalis muscles on the shape of the coronoid process were discussed. (See Figs. 3 and 4).

A conclusion which could be drawn from these theories is that orthodontic force directed to changing the shape of bone rather than the movement of teeth would have much the same effect on bone as muscle force. However, orthodontic stability and retention would be a problem because of the unbalancing of the new system after the cessation of the orthodontic force. Probably this is why orthodontic force influencing the growth of both bone and musculature into a balanced and harmonious system may be successful, whereas attempts to change the bone formation in an adult are usually not possible.

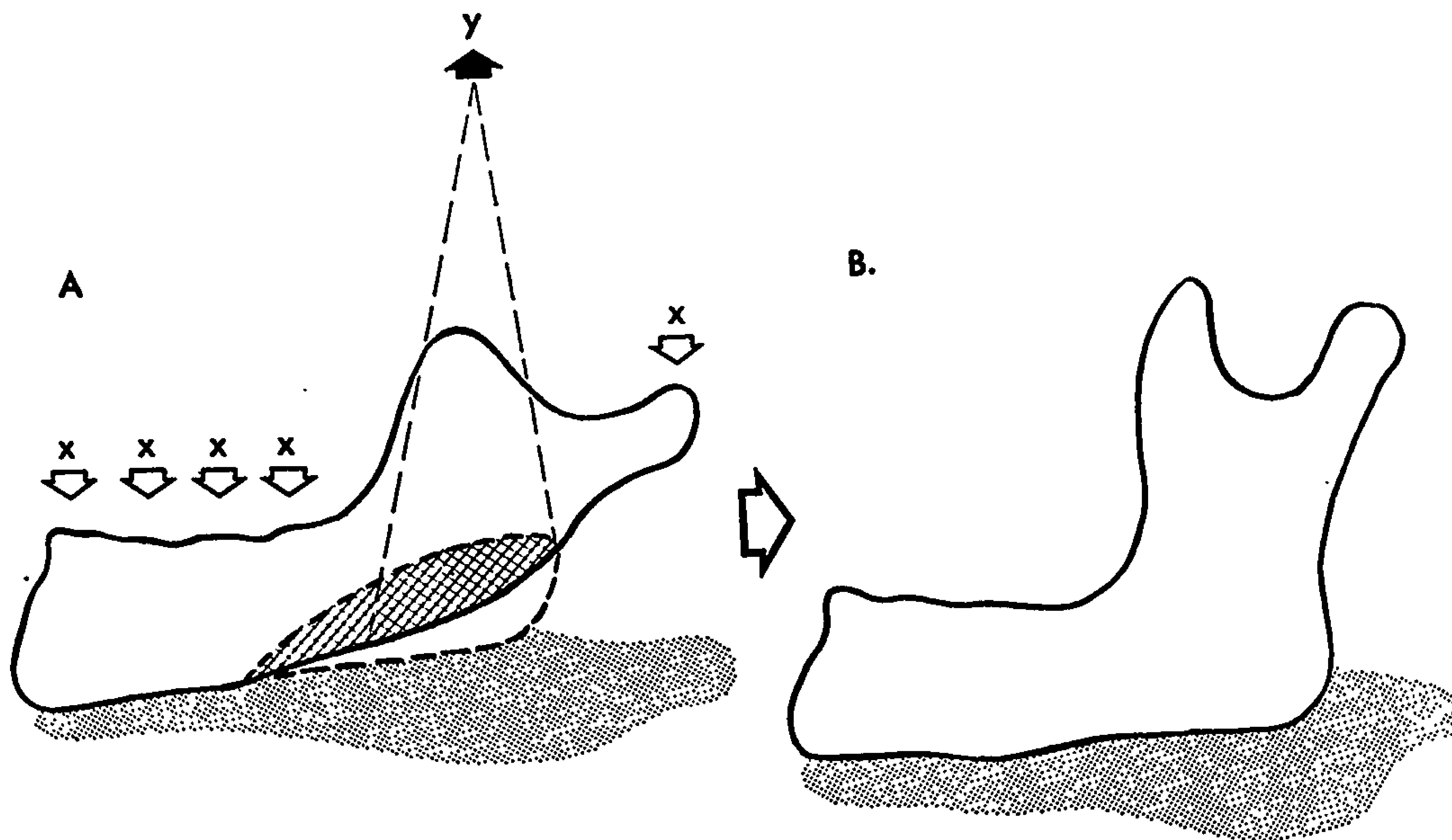


Fig. 3 - A: An infant mandible seen from the left side, where (X) indicates reactions and (Y) indicates the muscle pull of the masseter and internal pterygoid. When these muscles contract, the posterior-inferior angle of the mandible is deformed minutely in the direction indicated by the dotted line at the top of the shaded area. Thus, the surface tends to become less convex (more concave) with respect to its resting shape. This leads to osteoblastic drift, which adds bony material to the angle, tending to produce the modified (adult) shape shown on the right (B) and suggested by the dotted line below the unshaded area in A. (Not to scale)

(After Epker and Frost 1966 [38]).

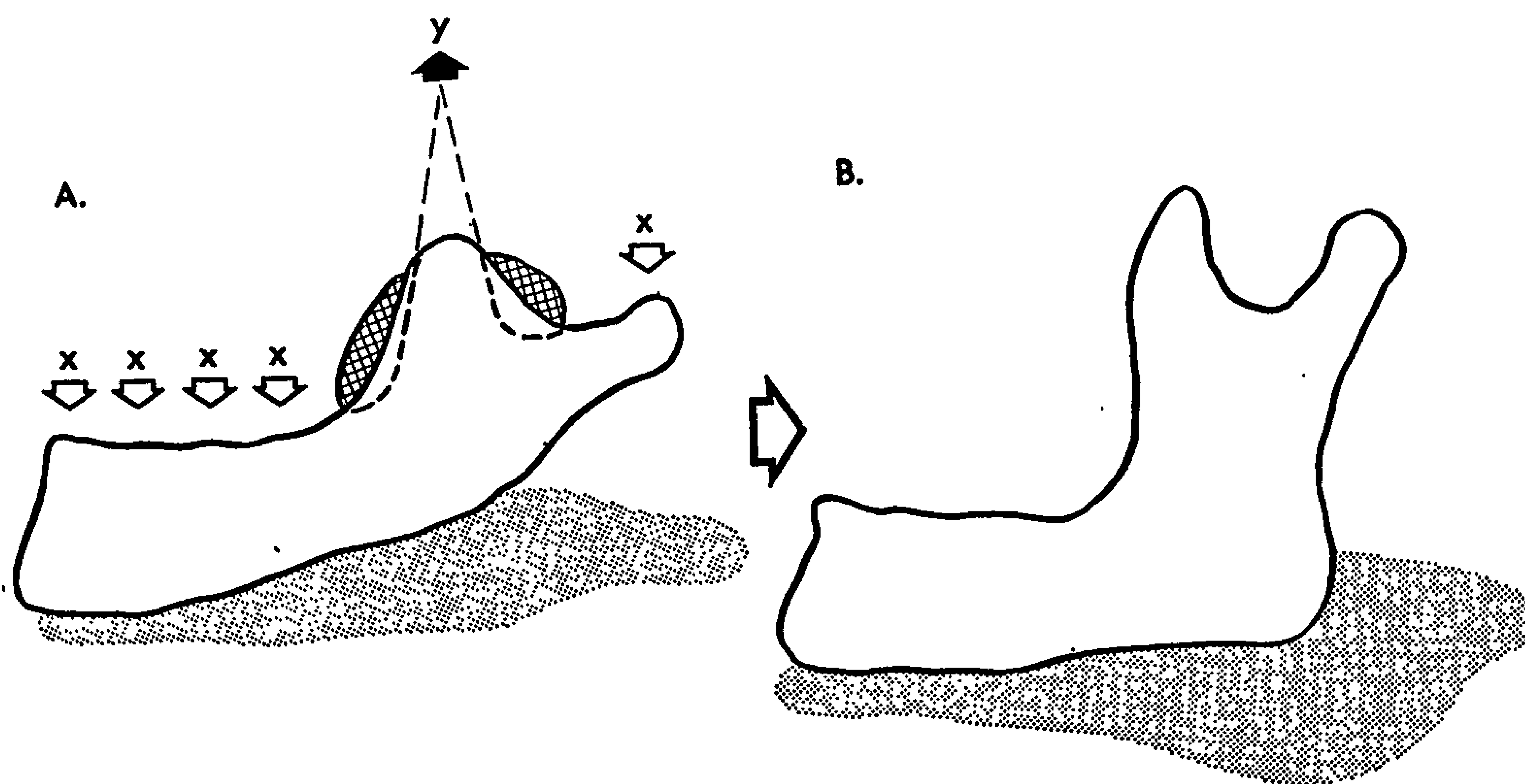


Fig. 4. - Symbols have the same meaning as in Fig. 3, except that here the temporalis muscle force is illustrated. The pull of this muscle tends to make the surface adjacent to its attachment bulge upward, as suggested by the shaded region on the left and right of the attachment. This is an increased convexity (decreased concavity) with respect to the resting shape, which causes osteoclastic drift. The surface is reshaped as suggested by the broken lines in A, and as shown in B. The actual changes in contour caused by the muscle forces are minute and are greatly exaggerated in the left drawings in A and B for illustrative purposes. It is important to recognize that the changes in contour are with respect to the resting shape (the shape when no muscle forces act on the bone).

(After Epker and Frost 1966 [38]).

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Further Experimental Works on Piezoelectric Effects.

De Angelis 1970 [31] conducted experiments on rats by separating the maxillary incisors with rubber segments after injecting tritiated proline as a label. The animals were killed after 2 hours.

He sought to find why (i) pressure causes one type of cellular response and tension causes another type of cellular response; (ii) why bone surfaces distant to the periodontal membrane, i.e. outer labial and lingual plates, are altered by orthodontic force.

It was found that the tension side of the socket was labelled and the pressure side was devoid of label. In the adjacent marrow spaces the side nearest the pressure was labelled and the side farthest away was devoid of label. The opposite was seen on the tension side. On the side of pressure, the outer labial plate was labelled.

De Angelis concluded that the minute bending and distortion of the alveolar bone was transmitted through the marrow spaces to the labial and lingual plates. This distortion would set up stresses and cause the piezoelectric effect to operate.

He did not mention the trabeculae in his theory and was not specific how the stress passed across the marrow spaces to cause the deposition and resorption of bone on distant surfaces. He did mention that convex and concave

surfaces have different charges when "under compression due to varying stress patterns" but did not carry his explanation or theory any further in this regard.

De Angelis speculated that the differential force theory of anchor teeth being related to root area was in fact related to differential alveolar bending and that the anterior alveolar process being thinner would bend before the thicker, buttressed posterior alveolar process. He concluded that the greater strain induced in the more distorted anterior alveolus would cause a greater piezo-electric response therein. On this theory, the buttressing of the posterior section of the alveolus would have been in response to an earlier piezoelectric effect during growth.

Norton [89] in 1972 presented the results of experiments in growing bone from freshly removed rat calvaria in tissue culture in an electric field with a potential of 490 volts. There was a growth pattern after 6 days on the negatively charged side facing the positive arch. Again this demonstrates electrical stimulation of osteogenesis.

Norton and Moore [90] in 1972 reported again in more detail an experiment on rat calvaria involving induced growth. Fresh bone was used in a tissue culture. Oscillating D.C., of a peak 490 V to a base 13 V providing

an electric field in 4 different sets of grids, was applied. Growth occurred in all 4 sets of voltages, on the negatively charged surface of the bone facing the positive grid.

The authors interpreted the results as being an example of reversed piezoelectric effect. The collagen fibres of the new growth were oriented in the electric field. They thought that an induced reversed piezo-electric effect was more likely than a direct electric effect on the growing bone.

Piezoelectricity in tooth structure.

Enamel and dentine were tested for piezoelectric properties by Braden, et al. in 1966 [22]. They used elephant enamel and wart-hog dentine so that relatively large specimens could be used in the experiments. Apatite crystal was also tested. Braden, et al., could not find any piezoelectric effect in the apatite or in the enamel. They stated that dentine gave results comparable with bone and hypothesised that the differences observed between enamel and dentine may be due to the fact that enamel has no collagen.

Stress-Induced Piezoelectric Effects in the Tooth-Alveolar Bone Complex.

In 1967 Cochran, Pawluk and Bassett [30] were the first to observe stress-generated electric potentials in the mandible and teeth as an integral mechanical unit.

They used fresh bovine mandible, kept moist with Ringer's solution. Axial loads up to 10 kg. were applied and in other experiments a second load perpendicular to the plane of the cut section was applied manually to the tooth. Strips of mandibular cortex, segments of lamina dura and longitudinal sections of teeth 1 - 2 mm. thick were tested separately.

Voltages of the value of 0.5 - 5 mV were recorded during bending of the separate specimens of tooth, lamina dura and cortex. The concave or compression side of these specimens was negative with respect to the other regions. The voltage was proportional to the load and peaked as loading was completed and decayed to zero if the load was maintained. After complete decay of this voltage, removal of the load generated a second voltage of opposite polarity and approximately equal amplitude.

When testing large sections of mandible, which included several teeth, no significant voltages were recorded during axial compressive loading of the tooth with electrodes placed on the mandibular cortex or exposed lamina dura. When these sections were cut to approximately

1 cm. in thickness, voltages were obtained from the same areas. These voltages increased with the applied load and were similar in characteristics to those voltages obtained from the separate specimens tested by bending.

Cochran, et al., attributed the difficulty in obtaining results, from the larger sections, to the great rigidity of the mandible in relation to the relatively small applied forces. Also, they stated that the greater volume of moist bone between the electrodes may have allowed a greater voltage leakage. They point out that charge leakage takes place in moist bone and that the recorded voltage in this type of experiment is not the full measure of potential difference induced by the mechanical stress. They state that the voltages of 1 - 5 mV recorded "probably" have biologic significance.

They stated that the "cut surface of a tooth was consistently negative with respect to surrounding bone". They did not specify if the surface was enamel, dentine or cementum or specify that all three surfaces gave the same result.

They found that if the electrode position remained fixed and the specimen rotated upward or downward in the clamp used in the experiment so that the direction of the applied load to the long axis of the tooth was altered, then the polarity and magnitude of the voltages altered.

Also, voltages obtained by axial loading were altered by the simultaneous application of a second force perpendicular to the specimen.

Cochran, et al., attributed the recorded voltage wave forms to piezoelectric effects rather than to artifacts. They maintained that (i) the wave forms had a consistent differentiated pattern that is not typical of artifact signals; (ii) the results paralleled those from a series of 160 experiments on canine femoral bone where there was a voltage output that maintained a consistent linear relationship to load. The voltage output also maintained a consistent relationship to deformation. These relationships are typical of piezoelectric effects; (iii) tests involving random movements of electrodes, exposure to external interference, and bending of non-piezoelectric material did not produce significant voltage signals similar to those recorded in the tests from the bovine mandible.

Cochran, et al., state that electric currents are generated during mastication, deglutition and by haemodynamic action within bone. They suggest these currents may play an important role in the normal physiology of the tooth and surrounding structures.

They draw a parallel between the electrical manifestations of the force applied in their tests and that force used in orthodontic procedures.

Gillooly, et al., 1968 [40] published the results of experiments concerning the electric response of alveolar bone to forces applied to a tooth. Fresh preparations of dog mandible, with teeth intact, were used.

Compared to accepted optimal orthodontic forces, they used relatively high forces of between 1000 and 2000 grams because of the insensitivity of their recording apparatus at lower force levels. The recordings were taken occlusal to the centre of rotation of the tooth. It was found that if the bioelectric potential difference was recorded from the side of the mandible towards which the force was directed the cortical plate became negatively charged with respect to the cribriform plate. Reverse polarity was noted on the opposite side of the tooth. Also, if a potential difference was noted between the cortical plates on both sides of a tooth, the cortical plate towards which the force was directed was negatively charged in relation to the cortical plate of the opposite side. In respect to the cribriform plates, the plate to which the force was directed became positively charged in relation to the cribriform plate of the opposite side. When the direction of the force on the tooth was reversed,

the polarity produced was also reversed.

Gillooly, et al., maintained that these results conformed with the idea that, under their experimental conditions, the cortical bone was compressed and the cribriform plate was under tension on the side towards the direction of movement and on the opposite side the cribriform plate was compressed and the cortical bone was under tension. They considered that the bone on the side of the tooth towards which the force was directed was deformed by pressure from the tipping tooth while on the opposite side the bone was deformed by the tension in the periodontal fibres.

They recorded an increase in peak potential as force was increased. However, the increase in potential between the cribriform plates was much less than the increase in potential between the cortical plates.

These results of Gillooly, et al., were in agreement with their expectation that areas of probable bone deposition should become negatively charged and areas of probable bone resorption should become positively charged.

Also, the basic contention of Bassett and Becker 1962 [7], that bone develops a negative charge in areas of compression, was supported by these results.

In 1973 Zengo, Pawluk and Bassett [159] published results of experiments undertaken to determine the nature of the electromechanical relationship between the tooth and its supporting structures. Also they sought to relate the polarity of the stress-induced potentials with histologic responses known to occur during orthodontic tooth movement and function.

Intact canine mandibles, kept moist with Ringer's solution, and with soft tissue removed, were sectioned in various planes for testing. Sections from labial, lingual, mesial and distal socket walls, whole and sectioned human and canine teeth as well as small sectioms of canine enamel, dentine and cementum were also tested.

During the experiments tipping forces were applied from labial, lingual, mesial and distal directions and potentials were recorded from all regions of the bone surrounding the tooth. (See Fig. 5). Access for mesial and distal testing was obtained by extraction of the adjacent teeth.

A load range of 75 to 3000 gms. was used and the range of deformation was 0.1 mm. to 1.00 mm. All the measurements were made in a controlled-humidity atmosphere.

When tipping forces were applied, the largest voltages (.85 mV) were recorded from the upper third of the alveolar bone which was under the greatest deformation.

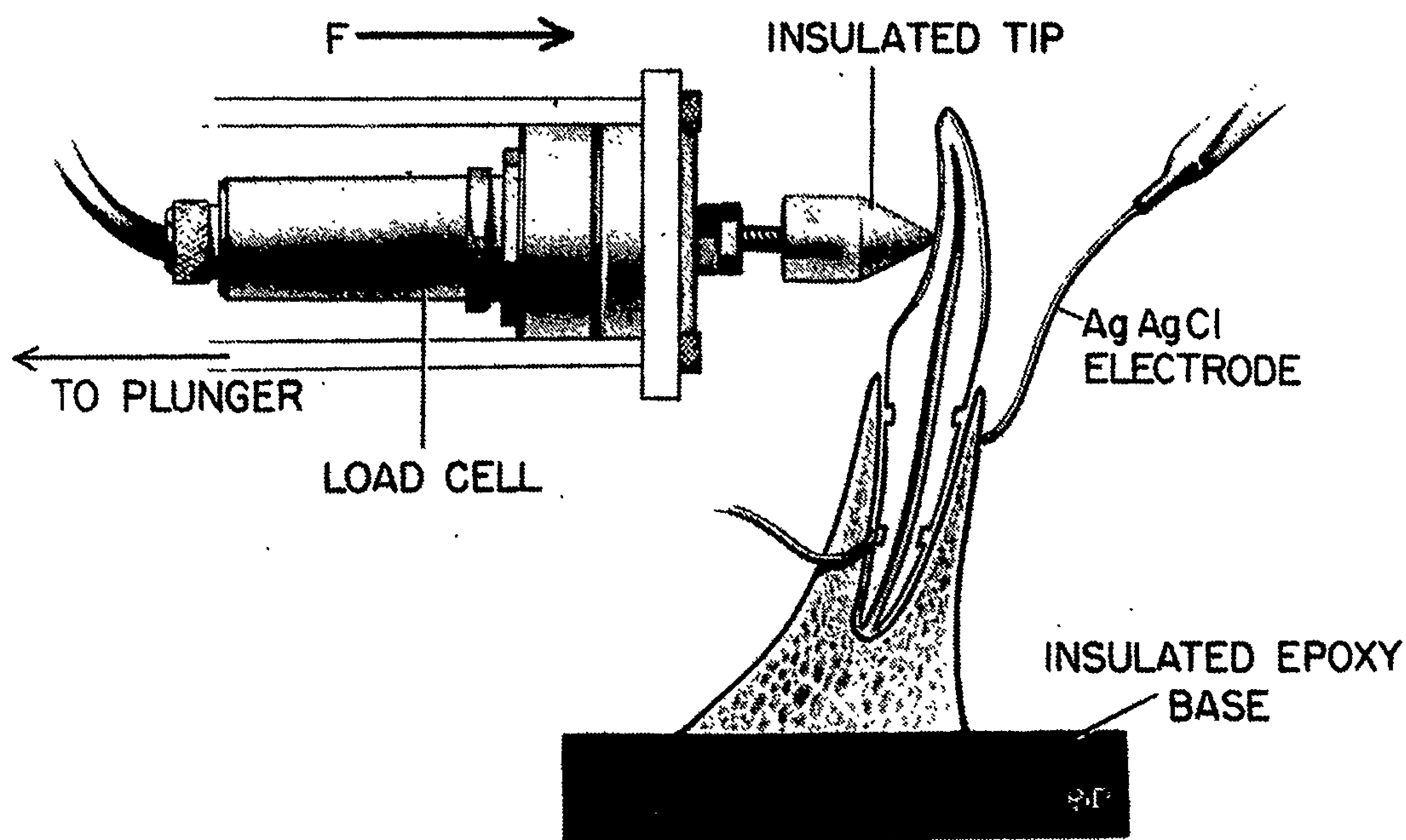

Fig. 5. Scheme of the relationship of the specimen to the deforming apparatus, load cell, plunger, insulated tip, and electrodes. Mechanical removal of a small amount of root dentine was performed to facilitate electrode placement on the inner alveolar wall. Insulated epoxy base employed to fix specimen within recording chamber.

(After Zengo, et al. 1973 [159]).

The voltages decreased to their lowest value (.18 mV) at the apex where the bone was thickest. The average drop was approximately 70%. (See Fig. 6). A reversal of polarity was observed as the electrode was moved apically on the outer alveolar surface. This occurred at the level of the horizontal centre of rotation of the tooth. (See Fig. 7).

A correlation between stress-induced electric polarization and histologic responses known to occur during orthodontic tooth movement was observed for a tipping force. (See Fig. 8A). The polarity of the root surface for a given force was the same as that of the outer alveolar bone surface on the same side. The polarity of the inner alveolar bone surface was the reverse of that on the root surface and the outer alveolar surface. Areas which were routinely electro-negative in these experiments were those in which osteoblastic activity is experienced during application of similar forces in active orthodontic treatment. Conversely, electro-positivity or electrical neutrality was recorded from areas where osteoclastic activity is observed under similar orthodontic movement.

An intrusive force, without significant tipping (0.25 mm. deformation) resulted in the polarities shown in Fig. 8B.

When the tooth was replaced in the socket with an

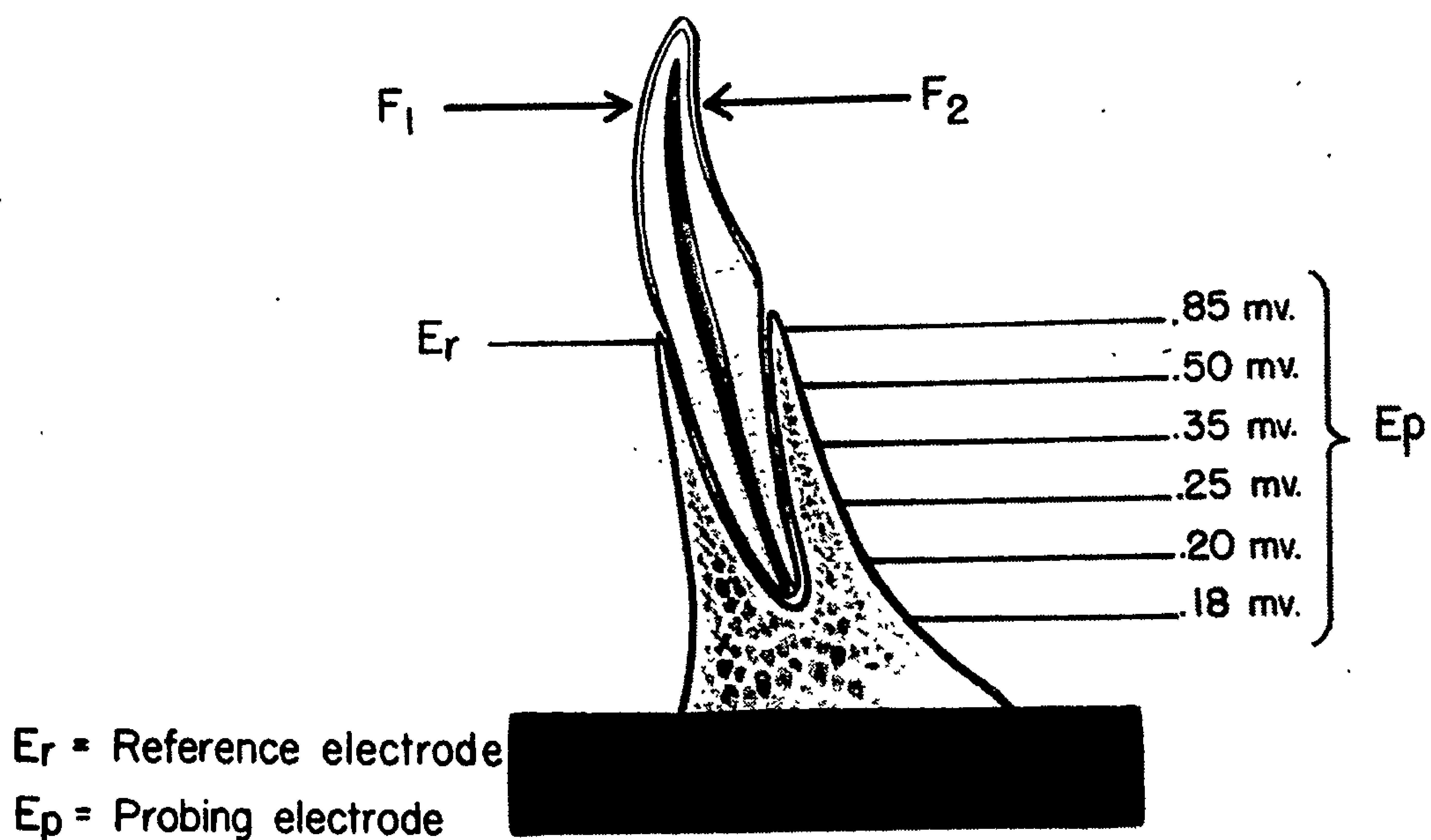

Fig. 6. Drawing depicting electrode positions and force directions. The potentials for a given deformation decreased from the alveolar crest to the alveolar bone in the apical region.

(After Zengo, et al. 1973 [159]).

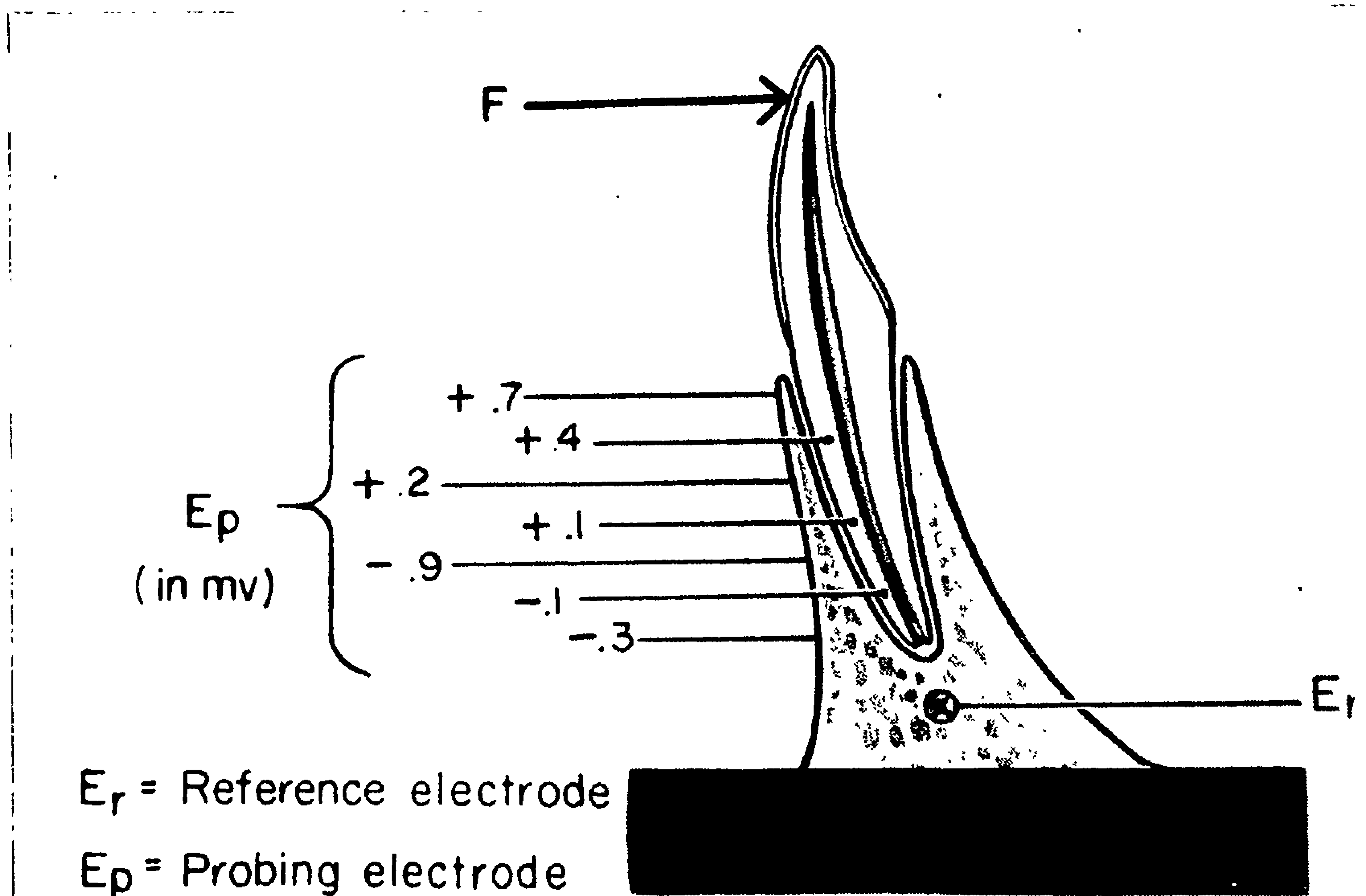

Fig. 7. Drawing depicting electrode positions, direction of force, and polarity measurements. The level at which the polarity reversed was in the region of the horizontal centre of rotation (tipping) for the tooth under investigation.

(After Zengo, et al. 1973 [159]).

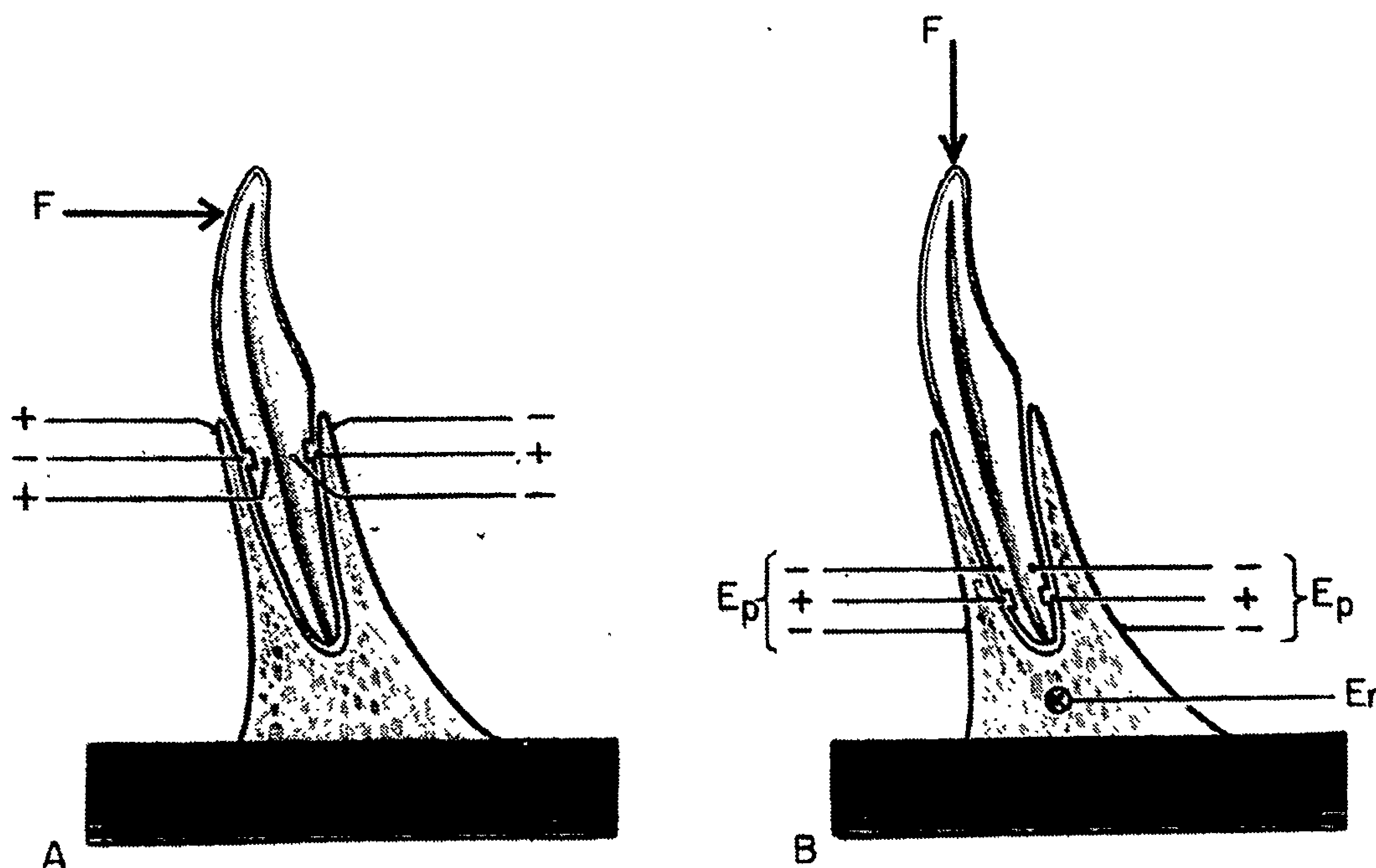

Fig. 8. A, Diagram depicting the direction of a tipping force and polarity measurements obtained. Note that the polarity of the inner alveolar bone surface was the reverse of that on the root dentine and outer alveolar surfaces. B, Diagram depicting the direction of an intrusive force, reference electrode (Er), probing electrode (Ep) positions, and the observed polarities.

(After Zengo, et al. 1973 [159]).

acrylic duplicate, the magnitude and polarity of the voltage of the alveolar bone did not significantly alter at the pressure side. However, there was a fall in the potential of the alveolar bone at the tension side which appeared to be due to the lack of periodontal attachment.

The sections of alveolar socket walls all gave a polarity under the bending test such that the convex surface of the specimen was positive in respect to the concave surface.

Large voltages (2.5 mV to 4.5 mV) were recorded from the enamel of stressed teeth. However, when the coronal dentine was mechanically removed the potentials from the enamel surfaces were only 5% to 10% that of the original potential.

When specimens of tooth structure and bone were tested in tension, dentine gave the highest potential of 1.0 to 2.5 mV and enamel the lowest, 0.1 to 0.25 mV.

The results of a test on any one specimen were reproducible to within a 10% variation. When the quantitative result did vary, the qualitative result was still constant, i.e. the polarity remained constant.

Zengo, et al., state that in regard to polarity, positivity can be relative. A region can be positive in relation to another because the first region has fewer electrons but can become negative in respect to another

region when it possesses more electrons than the latter region.

The force required to produce a measurable electric potential from the tooth - alveolar bone complex was well within the range of forces used for clinical orthodontic movement and also in function. Electrical potentials were recorded with forces as low as 75 gms.

The large potential response from the enamel of the teeth was queried by Zengo, et al. It was theorised that it may be due to a shear stress at the dentino-enamel junction between the dentine and enamel because of the different properties of these two materials, or the two materials may be acting together as a piezoelectric bimorph to give an increased potential.

They state that their results are in conformity with the theories advanced by Epker and Frost that changes in the surface curvature of bone caused by loading relate to specific cellular responses. They claim that their interpretations fit in with the hypothesis that Wolff's Law is an example of a negative feed back system. In this system mechanical energy is transduced to electrical energy which could regulate alveolar responses in such a way as to alter the bone structure.

Zengo, et al., likened the interproximal alveolar bony plates to cantilevers, thin at the tip and broad at

the anchored base. When subject to bending, the compressive load at the "leading" edge deforms the alveolar bone convexly towards the root, and at the "trailing" edge the periodontal fibres distort the alveolar bone with the concavity towards the root.

They claim that the current "pressure-tension" hypothesis is sufficient to explain only the intermediate steps in the transfer of applied forces to the surrounding alveolar bone but does not clearly define the resultant mechanical or electrical behaviour of the alveolar bone.

ELECTRO-MAGNETIC FIELD MECHANISM THEORY OF BONE REMODELLING.

Johnson 1964 [62] has proposed a theory of bone deposition and resorption. He hypothesises that the three controlling factors - mechanical, circulatory and metabolic - initiate a common electrical signal to activate the bone cells. He theorises that in normal conditions all three factors would operate, but in extraordinary circumstances one factor could alter the balance and effect a change.

Mechanical Factor.

He subscribes to the basic piezoelectric theory of Bassett, Fukada and Shamos in relation to the mechanical factor.

Circulatory Factor.

When stating his theory relative to the circulatory factor he differentiates two types of hyperaemia - active and passive. He states that when active hyperaemia occurs the tissue is normal in appearance and the dilated capillary bed is flushed and pink. The blood flows rapidly, lymphatic flow is reduced, and there is minimum loss of oxygen, sugar, proteins and all nutriments to the tissue in the traverse between the supplying arterioles and the draining venules. The high oxygen tension

supports osteoclastic activity.

He further states that passive hyperaemia is found in oedematous tissue. The capillary bed is dilated and is blue and cyanotic. Lymphatic flow is increased, blood flow is slowed and there is maximum escape of oxygen, sugar, protein and nutriments to the tissue in the traverse between the arterioles and venules. Passive hyperaemia produces high tissue fluid protein and induces osteoblastic activity.

Johnson distinguishes between the two types of hyperaemia and their effect on bone from the differences in flow rate. He claims that the capillary bed is controlled by the "glomoid" system acting through a series of chemoreceptor sensor cells. He states that regions of hyperaemia show a potential difference to areas of normal flow and also that active and passive hyperaemic areas show opposite signs of potential difference. He quotes Burr, et al. (1940) who measured the potential difference in normal tissues (unspecified) near a wound which first exhibited active hyperaemia, then passive hyperaemia four days later. The normal tissue exhibited positive potential difference at first, and negative potential difference for the latter period in relation to the hyperaemic area.

Metabolic Factors.

Johnson states that the metabolic factors which support the osteoblastic or osteoclastic activity are thought of as acting through chemical reactions and calorie productions. He then states that the oxidation-reduction reactions of metabolism can be expressed in a series of increasing and decreasing potential differences. He quotes Schmitt as pointing out that a simple conversion of sugar to carbon dioxide and water involves potential differences across the interfaces of cell organelles equivalent to 10,000 volts across condenser plates 1 cm. apart. Further, Schmitt suggested that intracellular metabolism consisted of flowing electron fields that transfer energy.

Therefore, Johnson states, alteration of bone metabolism may be reduced to changes of potential difference altering cell behaviour. Also, application of an electric current or an electric field may change the rate or sequence of metabolism.

Johnson sums up his theory as follows:- "Cell activity is ordered and controlled by the field in which the cell is active. A field is the summated product of activity of a neighbourhood of cells - of their products

as matrix, excreta, electrolyte binding or release, and potential differences. To this intrinsic cellular generation of a field is added mechanically-induced point specific piezoelectric signals, circulation-induced regional potential differences and constitutional settings of metabolic oxidation-reduction potentials. The end result is an integrated, graded electro magnetic field which signals the appropriate cell modulation at the appropriate site and time."

VASCULAR THEORIES OF THE MECHANISM OF BONE RESPONSE TO ORTHODONTIC FORCE.

A theory that bone deposition and removal was caused by a vascular mechanism was propounded by Trueta in 1963 [141].

He first discussed the blood supply to bone. There is usually only one nutrient artery of long bones supplying the whole shaft up to the epiphysial cartilage. It also supplies the sinusoidal system of vessels in the bone marrow. At the end of growth the perforating vessels of the epiphysis and metaphysis anastomose with each other and with the main nutrient artery.

The periosteal vessels were studied also. By interrupting the nutrient and metaphyseal vessels necrosis of the inner two-thirds of the cortex was caused. Isolating the periosteal vessels with a plastic sheet caused the death of the outer third of the cortex. With the aid of electron microscopy it was found that a number of Haversian canals carried two vessels, one smaller than the other. Trueta suggested that this pointed to one vessel being an artery and the other a vein, so that blood can flow in both directions in some Haversian canals.

Mechanics of Bone Circulation.

He stated that there was a sinusoidal system of blood vessels interposed between the arterioles and veins in the

rigid compartments of the bone marrow and this caused so great a drop in the cardiac vis-a-tergo in the veins leaving the bone, that, without other contributing factors, the blood circulation in the bone would come to a standstill. The main one of these factors was repeated, intermittent muscle contraction. Under both experimental and disease conditions of muscular inactivity or atrophy, sinusoidal and venous engorgement and bone rarefaction have been observed. As soon as muscle activity was restored, it was found that venous engorgement ceased and new trabeculae were laid down. Trueta gave examples of both effects. In the case of muscle inactivity he instanced poliomyelitic paralysis, flaccid paraplegia, osteoporosis after fracture, and plaster immobilisation leading to bone rarefaction. Muscle over-activity caused bone deposition as in the case of spastic paraplegia or accompanying the muscle spasm of severe osteoarthritis of the major joints.

He stated that it is not yet clear how the local changes of circulation stimulate bone formation or bone removal. The presence of oxygen seems to be vital to bone formation and when the supply ceases the formation of new organic matrix ceases.

The Theory of Induction in Osteogenesis.

Trueta hypothesised an unknown substance, which he

named a "vascular stimulating factor" (V.S.F.) or osteogenetic substance, was released from dying or suffering chondrocytes, osteocytes and endothelial cells and was responsible for the process of osteogenesis.

He reported the experiments which he had performed on vascularity of the callus of fracture. It was found that the vessels from the soft tissue surrounding the fracture progressed towards the area of devitalised bone at the end of the fragments and towards the hypertropic cartilage cells. Trueta claimed that this pattern of vessel growth was in response to the V.S.F. liberated from the damaged cells.

He summarised his belief that the vessels caused osteogenesis by stating that the endothelial cells of the walls of the advancing vessels divide along large sections of their walls as well as at their extending ends and as a result lay down osteoblasts or their progenitors. All these cells from endothelium to osteocyte remain attached by intercellular cytoplasmic connections. After the deposition of collagen and polysaccharide matrix by the osteoblasts and their subsequent surrounding by apatite the cytoplasmic attachments to their ancestors prevent the mineral from forming an isolating wall. Thus, canaliculi will appear around each of the cell expansions and the original syncytium will be preserved by the rigid mineral

structure characteristic of bone.

Effects of Compression on Osteogenesis.

Trueta conducted animal experiments and found that excessive compression stimulated osteogenetic activity of the vascular wall and caused an increase in bone deposition in the compressed area, with concomitant reduction of the vascular lumen after each new ring of osteoblasts had become incorporated into the new bone as osteocytes. Finally, large areas of bone were deprived of circulatory blood and bone. Sclerosis occurred, with alternation of dead and living bone. The death of the osteocytes was caused by the final obliteration of the arterial blood vessels from which they received their nourishment. In osteoarthritis of the hip in humans, the areas of increased bone density are close to the areas that are more vascular. This is believed to be the mechanism of bone sclerosis.

Bone Removal and the Osteoclasts.

Trueta stated that reduced apposition of bone or its increased resorption can be produced by withdrawing from the blood some of the essentials required for bone formation, such as oxygen, vitamins A, C and D and calcium and phosphate salts. His view was that osteoclasts are formed by fusion of the cells, presumably intermediate cells,

osteoblasts and osteocytes. He pointed out that in bone resorption caused by muscle inhibition osteoclasts were abundant. But he asked were they the initiators of bone removal or a simple consequence of the resorption of bone.

Trueta believed that the initial bone resorption caused by the vascular mechanism accounted for the appearance of the osteoclasts.

MUSCLE BLOOD-FLOW AND CIRCULATION IN BONES.

The phenomenon of the correlation between muscle blood flow and circulation in bones was demonstrated by Trueta's experiments (1963 [141]). The orthodontic significance of this finding is that a normally active oro-facial musculature is necessary for normal growth and bone reshaping by orthodontic force. Where there is any impairment of this muscular activity, bone response to applied force could be affected.

Further to Trueta's investigations, Shaw 1966 [118] conducted animal experiments to examine the relation between circulation in bone and in the overlying muscle. The femur and overlying muscles of adult cats were studied. The femoral nerve was isolated and divided.

A simultaneous rise in arterial pressure, intra-medullary pressure and blood flow, and in muscle blood flow occurred when the proximal end of the femoral nerve was stimulated. Shaw ascribed this result to a central effect on arterial pressure. He was surprised by the sudden increase in intramedullary pressure and blood flow.

There was a fall and subsequent rise in muscle blood-flow and bone blood-flow during continuous stimulation of the distal cut end of the femoral nerve. Shaw suggests that during muscle contraction the pressure on the muscle

veins empties them, and that sustained or rapidly repeated contraction increases muscle blood-flow by arteriolar and capillary dilatation, probably caused by products of local metabolism. Shaw states that the nerve stimulation did not have a direct effect on bone blood flow but ascribes a passive role to intermedullary blood vessels during phases of varying blood flow in muscles.

FLUID DYNAMIC MECHANISMS.

In 1966 Bien [19] proposed his theories of Fluid Dynamic Mechanisms which regulate tooth movement in response to applied force. He wrote that the periodontal membrane has four morphological components:- cells, vessels, fibres and interstitial fluid and each contributes to the fluid transmission of force applied to the crown of a tooth. These forces are from mastication, swallowing, as well as orthodontic and prosthetic appliances. Bien contended that a tooth does not undergo free oscillation in its socket as a result of the application of force, because of a hydraulic damping effect due to fluid being forced through fine orifices in the tooth socket or due to a viscous frictional drag.

He observed the different response of periodontal tissue to orthodontic force and to hard chewing. He quoted Schwarz's optimal orthodontic force of 25 - 30 gms. per sq.cm. as well as the fact that no harm results from a biting force of 1500 gms/sq.cm.

Bien stated that within the periodontium three distinct but interacting fluid systems are involved in pressure control: (i) the vascular system enclosed within the blood vessel and lymph vessel walls, (ii) the system of cells and periodontal fibres, and (iii) the interstitial

fluid which is continuous and permeates the spaces between the cells, fibres, blood vessels, tooth and bone.

He conducted a series of experiments concerned with the intrusion of teeth on humans and animals. He stated that the non-Hooke type characteristics of the results of these experiments showed that the teeth are not suspended in the socket by a rubber-like material or by fibres. His results also showed that several mechanisms were involved in tooth support.

Squeeze Film Effect.

Bien compared the periodontium to a microscopically-thin viscous lubricating film between flat plates known as a non-rotating bearing. These films are capable of withstanding large pressures.

He stated that as the capacity of the periodontium to sustain the load was shown to be a function of the rate at which a force is exerted against a tooth, the squeeze film was studied for both momentary and sustained effects, i.e. for functional and orthodontic forces. Momentarily, the fluid trapped between the tooth and the socket tends to move to the boundaries of the film at the neck and the apex of the tooth, while acting to cushion the load. When the force is removed before all of the fluid is squeezed from between the tooth and the bone, the replenishment of the film occurs both from diffusion through

capillary walls and through recirculation of the interstitial fluid. Under light sustained orthodontic force, interstitial fluid equilibrium can be reached but under strong sustained orthodontic force capillary pressure is insufficient to counteract the applied force and cannot replenish the squeeze film. The load-carrying capacity of a true squeeze film is known to drop off rapidly as it becomes relatively very thin.

Spring Effect of the Periodontium.

If Bien's theory explains the mechanism of the initial intrusion of the tooth, then other hydrodynamic phenomena must occur as the intrusion is continued. He proposed that, with further intrusion of the tooth, the periodontal fibres tighten, then compress and occlude the vessels which run between them. Ballooning of the vessels then occurs causing cirsoid aneurisms due to the back pressure of the arteries which are partially embedded in the bone. The high pressure in the aneurisms tends to force fluid through the walls of the vessels. Beyond the stenosis, there is a vascular pressure drop which allows formation of minute gas bubbles (oxygen), which diffuse through the vessel walls. Bien theorised that the cirsoid aneurisms being minute flexible walled sacs of fluid act (i) as minute springs, (ii) to replenish the squeeze film, and (iii) to dissipate kinetic energy by

forcing fluid through the vessel wall.

This observation is in accord with the findings of Picton 1965 [99] that fluids transmit the force from the tooth to the alveolar walls.

Haemodynamic Activity during Tooth Movement.

Bien referred to Trueta's 1963 [141] theory that bone deposition and resorption are due to a vascular rather than a cellular mechanism and recalled that Trueta pointed out that the vascular mechanism theory did not "explain" the deposition and resorption.

Bien suggested that during mastication only a few gas bubbles can be formed due to the short duration of the applied force which is damped by the squeeze film that is returned as the force is released.

But he hypothesised that with prolonged forces, such as orthodontic forces, acting, then oxygen bubbles occur past the constriction of the capillaries and small vessels, where they are caught between the periodontal fibres. Minute free gas bubbles form in the interstitial spaces from the diffusion through the vessel walls. As well as going back into solution, these minute gas bubbles may become lodged under and between spicules of bone having many crevices with a small radius of curvature, thereby creating a favourable local climate for bone resorption.

Bien considered the periodontal arterial and venous

retia which are located at the gingival border and base of the socket to be areas where the gas cavitation could occur.

These systems of arterial loops and arcades are well designed to withstand the high periodontal pressures induced by mastication. When inflammation occurs, the loop pattern appears to change to anastomoses, with a consequent lowering of periodontal pressure. Bien theorises that under these circumstances gas cavitation could occur, followed by bone resorption. The inflammation could be the result of excessive prolonged force such as orthodontic force. The vascular changes in the rate return to normal following palliative treatment, as Bien observed histologically.

MECHANOCHEMICAL HYPOTHESIS FOR BONE REMODELLING.

Justus and Luft 1970 [63] presented a mechanochemical theory to explain bone deposition and resorption in response to applied force and they conducted experiments on the solubility of stressed hydroxyapatite crystals to test this hypothesis.

They proposed that bone responds to mechanical stress by differential growth to resist the applied stress and therefore mechanically induced bone remodelling is probably regulated by a negative feed back system.

Their hypothesis was that a change in the loading of bone results in an altered straining of the hydroxy-apatite crystals in bone. This in turn alters the solubility of the crystals, providing the required negative feed back message to the bone cells in the form of a mechanically induced chemical change. Provided the bone cells were sensitive to calcium, the cells would then either deposit or resorb bone substance as needed, to accommodate the bone to the applied stress. Justus and Luft stated that a high cellular sensitivity to calcium has been reported.

In their experiments synthetic hydroxyapatite crystals were subjected to tensile instead of to compressive stress, because of technical difficulties. Relatively large

single hydroxyapatite crystals such as they were obliged to use for the experiments are fragile and break easily under compressive forces. It was pointed out that the hydroxyapatite crystals in bone are seldom subjected to tensile stress.

They stated that when a sudden tensile strain is produced in an ionic solid which is in equilibrium with a solution, the probability that an ion will escape from the solid into the solution becomes higher, i.e. the solubility of the solid increases. This is because tensile strain diminishes the bond energy between the molecules of a solid. In addition the strain which separates the molecules at the surface of the crystal lattice brings more solvent into contact with the surface of the crystal and reduces even more the lattice bond forces at this surface.

Conversely, if a sudden compressive strain occurs in an ionic solid in equilibrium with a solution, the solubility of the solid should decrease.

The hydroxyapatite crystals in the experiments which were subjected to tensile forces did show a significantly increased solubility.

They theorised from this result that a pure compressive strain in hydroxyapatite crystals would demonstrate a decreased solubility.

No relationship between the amount of deformation and the solubility could be observed in the experiments. This should have been the case, provided the deformation was inside the elastic range of the crystals. Justus and Luft theorised that this lack of correlation could have been due to difficulty in aligning the crystals in respect to their crystallographic planes and the application of stress.

Justus and Luft offered no experimental confirmation of the cellular sensitivity to calcium but theorised that their idea of mechanochemical negative feed back system was more likely than the piezoelectric hypothesis of Becker, et al., 1964 [13], Shamos and Levine 1964 [113], and Bassett 1965 [6].

HYDROSTATIC - BONE DEFLECTION THEORY OF BONE RESPONSE TO ORTHODONTIC FORCE.

Baumrind 1969 [9] conducted a series of experiments designed to test theories which postulated that movement of a tooth within the periodontal space in response to applied force, generated a "pressure" side, where cell activity decreased as a result of vascular constriction, and a "tension" side where cell activity increased due to stimulation from stretched fibres of the periodontal ligament.

He referred to and took issue with the early theories of Oppenheim 1942 [94], Sandstedt quoted by Schwarz 1932 [109], Schwarz 1932 [111] who maintained that all tooth movement occurred within the periodontal space.

Baumrind disagreed with the statements of Gottlieb 1942 [41], 1946 [42], that it is impossible to perform orthodontic treatment without the moving teeth contacting the alveolar bone.

He investigated also whether cell metabolism was depressed on the pressure side and enhanced on the tension side.

He used rats as experimental animals in a sufficiently large number (99) to minimise chance results significantly affecting his findings. The smallness of the experimental sample was one of his criticisms of the previous theories.

Molar teeth were wedged apart with elastic, and, after 72 hours, pressure and tension areas away from the direct area of trauma of the elastic insertion were examined.

It was found that there was no difference in the direction of change of cell metabolism, between the pressure and tension sides. Cell replication rates increased on both sides and collagen synthesis rates decreased on both sides. Also, the general metabolic rate increased on both the pressure and tension sides.

With regard to the dimensional changes, Baumrind found that the average displacement of the crown of the first molar was more than ten times the average reduction in width (15 μ) of the periodontal space on the pressure side measured at the alveolar crest. The average increase in width on the tension side was only 4 μ measured near the tip of alveolar bone at the root bifurcation.

Baumrind concluded that these results can only be accounted for by bone deflection and that this deflection can be caused by forces lower than those required to produce gross reduction of the width of the periodontal ligament.

He stated that his experimental result showing the relative stability of the periodontal ligament under pressure compared to the bending of the alveolar bone,

was a refutation of theories based on the "squeezing-out" effect of fluids from the periodontal ligament on the pressure side. Notably, he referred to Bien's theory 1966 [19].

He observed undermining resorption on the tension side of the bone examined in his experiments. He claimed that this threw doubt on the pressure-tension hypotheses which postulates that undermining resorption is a feature of the pressure side due to the constriction of the vessels between the tooth and the alveolar plate.

He maintained that because the periodontal ligament is a continuous hydrostatic system, pressure applied to it will be transmitted equally throughout the system in accordance with Pascals Law. Also, that the bone will behave like any solid body when force is applied to it and will respond in accordance with Hooke's Law.

Baumrind offered his hypothesis that when orthodontic force operates on a tooth, the force is transmitted to all tissues in the region of the force, and each structure, i.e. tooth, periodontal membrane and bone, is deformed according to physical laws. He contended that the bone deforms more easily than the periodontal membrane and that when it does the stress is dissipated by stress lines in the deflected bone. Not only the lamina dura but the trabeculae are strained. The stress

thus initiates cellular activity to reorganise the deformed bone to resist the external force.

In support of his hypothesis he points (i) to the relative ease of tooth movement in children's less calcified and more flexible bone, compared to that of adults; and (ii) the rapidity of alignment of anterior teeth set in thinner, more flexible bone, compared with the molar area.

Baumrind did make the point that there were changes in the periodontal ligament when force is applied to a tooth but implied that the changes were too small to be significant.

He did not give any figures for the force generated by his experimental method of wedging with elastic.

Baumrind's results are significantly different from those of Botting and Storey 1973 [21], allowing for the difference in species of the experimental animals, in that he did not observe tooth bone contact. The force used by Baumrind may have been very light. If so, the relatively short time of application of the force (72 hours) would have been insufficient for tooth bone contact to occur, in the light of Botting and Storey's results (1973 [21]), obtained when using very light forces in their experiments on the guinea pig. They found that

it took 6 days for tooth-bone contact to occur, using 3 - 7 gms. of force.

Also Storey 1955 [129] found that in the rat a lateral force of 25 gms. on the maxillary incisors "almost" caused tooth bone contact after 7 days. He stated that separation of the premaxillary suture occurs in the rat when lateral force is applied to the incisor teeth. This may have occurred during Baumrind's experiments and influenced his findings.

EFFECT OF LOCALLY APPLIED HEAT AND ORTHODONTIC FORCE ON BONE.

Research into the effect of locally applied heat on bone has shown that bone will respond to this stimulation by greater cellular activity. This suggests enhancing effects are possible when orthodontic forces are applied in the presence of heat.

Spagnoli, et al. 1964 [125] experimented with the application of local heat to the mandibles of rabbits. Heat was supplied by a metal unit placed between the masseter muscle and the periosteum of the mandible, with projecting wires connected to the current source. A thermostat kept the temperature within 2.2 - 3.9 Celsius degrees above that of an unheated control element similarly inserted on the opposite side of the mandible. Heating was maintained for 4 - 6 hours daily for 5 - 10 days, averaging 50 - 60 hours total heating time.

Experimental difficulties prevented a definite result being observed, but there appeared to be an increase of bone formation around the heated elements.

In 1965 Bundy, et al. [24] varied the experimental technique by using induction as the source of heat. By this method a plate of metal, in this case vitallium, is heated without the necessity of wires having to be connected. These plates were placed beneath the masseter

muscle against the periosteum on one side of the mandible. The other side was used as a control. As well as the mandible, the parietal bone of rabbits was subjected to experimental heating.

Although the experimenters state that the temperature was "controlled" and "recorded" at all times and that a theromocouple was used for all temperature recordings, they fail to state what temperature was used in the heating.

They state that the mandibles were heated for 5 hours daily for 10 - 24 days.

The histological examinations showed that bony growth surrounding the heating units contained connective tissue, osteoid tissue, bony trabeculae and mature lamellated bone. The heated mandibular halves were heavier than unheated mandibular halves used as controls.

It was concluded that locally applied heat caused extensive growth of bone in the rabbit mandible.

The results from the parietal bones showed mainly formation of white connective tissue around both heated and unheated bones. No conclusion could be formed concerning the effect of heating the parietal bones.

Following those experiments, Tweedle and Bundy 1965 [142] experimented with the effect of local hyperthermia on tooth movement in the rabbit.

The upper incisors were separated by a helical coil

spring delivering a force of 85 grams. The right side of the maxilla of the experimental animals was heated. Two methods of heating were tried on different groups of experimental animals - heating by induction as in the previous experiment and by short wave diathermy.

The induction heating was maintained at 3.3 Celsius degrees above body heat. A vitallium plate was placed between the periosteum and maxillary bone over the right maxillary incisor root and induced eddy currents heated this plate.

This induced heat was maintained for four consecutive hours daily for from 4 to 10 days, giving a total heating time of 16 to 40 hours.

With the diathermy heating, no temperature was quoted, but Tweedle and Bundy state that two animals were heated at 160 mA for 20 minutes daily for 11 and 16 days, and another two rabbits were heated for 10 minutes daily at 90 mA for 5 and 8 days.

At the end of the first day the incisors of heated animals were separated nearly twice the distance of those of the control animals. (See Table I).

At the conclusion of the experiments, the animal with the longest diathermy time had the greatest angular spread. All the heated animals showed a greater linear separation than the controls. Induction heating

TABLE 1.

Linear and angular deflection of rabbit maxillary incisors, following local application of heat by induction or diathermy. Controls and heated incisors were fitted with a spreading appliance.

	Animal Number	Linear Deflection after First Day		Linear Deflection at Sacrifice		Angular Deflection from Midline at Sacrifice				Days Right Maxilla Heated		Duration Daily Heating Period	
		Heated	Control	Heated	Control	Right Heated	Right Control	Left Heated	Left Control	Heated	Control	Heated	Control
INDUCTION	1	1.1 mm	0.6 mm	3.3 mm	2.9 mm	7°	5°	5°	5°	4	0	4 hrs.	0
	2	1.2	0.5	4.0	3.1	8	6	6	6	4	0	4	0
	3	1.0	0.6	4.4	3.7	12	9	7	8	10	0	4	0
	Mean	1.10	0.57	3.9	3.2	9.0	6.7	6.0	6.3				
DIATHERMY	4	0.7	0.3	3.6	3.0	11	7	8	8	11	0	20 mins.	0
	5	0.8	0.4	3.7	2.9	12	9	9	8	16	0	20	0
	6	0.5	0.2	2.7	2.4	9	6	7	5	5	0	10	0
	7	0.6	0.3	2.8	2.6	10	7	8	6	8	0	10	0
	Mean	0.65	0.30	3.2	2.7	10.5	7.3	8.0	6.8				
	TOTAL MEAN	0.84	0.41	3.5	2.9	9.9	7.1	7.1	6.6				

(After Tweedle and Bundy 1965 [142]).

resulted in greater linear separation than that seen in half the diathermy heated animals. The heated incisor had the greatest deviation and mobility. There was greater separation of the intermaxillary suture in the heated animals and this separation was greatest in those heated longest.

Histologically, changes were seen in the alveolar bone and the periodontal membrane. The heated side of all experimental animals showed greater bone resorption. Osteoclastic and osteoblastic activity were more apparent in all the heated animals compared with the control animals. Osteoclastic activity and remodelling were more apparent on the pressure side.

Tweedle and Bundy state that the diathermy was harder to control than the induction heating and caused some necrosis. It also caused bilateral heating and tissue heating may have been above the optimum.

Their observations support the conclusion that locally applied heat resulted in an increased rate of tooth movement observed in the separation of the maxillary incisors of the rabbit. The total mean linear deflection of all heated animals at the conclusion of the experiment was 3.5 mm. and that of the controls was 2.9 mm. This indicates that the heating increased the mean linear deflection by about 20% over that of the control animals.

Tweedle and Bundy 1965 [142] suggest that "a procedure

might be developed in orthodontics to reduce overall treatment time and cost."

There is a probability that human tissue would respond to local heating and orthodontic force in a similar manner to that of the experimental animals. Wedlick 1967 [158] states that the metabolic rate increases with rise of temperature.

A suitable simple method of applying heat to the human jaws would have to be found. The rise in temperature required is between 2.2 and 3.3 Celsius degrees, as seen in the previously mentioned animal experiments.

Various methods of causing local heating in the human body were discussed by Wedlick 1967 [158]. He wrote that conductive heating by application of hot water or hot packs to the skin results in heat being conducted about 12 mm. into the body. Infra-red radiation does not penetrate much further than the surface applications and is virtually a form of conductive heating.

Short wave diathermy produces even deep heating through various tissues and can pass through bone. However, there is risk of increased heating and damage if metal lies in the field.

Microwave therapy will not penetrate more than 9 mm. through muscle tissue and therefore lacks penetration.

Ultrasonic energy penetrates more than three inches

into the soft tissues of the body, where 25% of its energy remains, but is stopped by bone.

Most of these methods are unsuitable for an orthodontic purpose:- Ultrasonic energy, because of lack of bone penetration; Microwave therapy because of a general lack of penetration; Short wave diathermy because of the risk of damage from overheated restorations and orthodontic appliances. Infra-red radiation would be awkward to apply in the posterior of the mouth and could be expected to have a marked drying effect on the mucosa.

It is conjectured, as a method of applying heat, that hot mouth washes about 4 times per day, would be satisfactory. Suggested times are - on rising, before going to school, on arrival home, and before retiring. Several tumblers of hot water would be used, retaining the water in the mouth for a time and swirling it around the teeth and alveolar processes.

The total time of contact would approximate that of the short wave diathermy applications in the animal experiments. The rise in temperature by conductive heating would have to be determined. This would be conditioned by the rate of conductivity of the oral tissues, both soft and hard, and, as Wedlick [158] infers, by the cooling effect of the increased blood flow.

As indicated earlier, these ideas are only speculatory at present.

THREE BASIC TYPES OF FORCE APPLIED TO BONE IN ORTHODONTICS.

Functional Orthodontic Forces.

Functional appliances, such as the oral screen and Andresen appliance, rely for their effectiveness on withholding or harnessing, and thus unbalancing, the natural muscular forces available in the oro-facial area (Hotz 1961 [55]). The object is to alter the skeletal units indirectly by first altering function (Valinoti 1973 [144]).

The force delivered by these appliances to bone is intermittent and this action stimulates the circulation and an increase in cell numbers is observed on the pressure and tension sides of the bony tooth socket. On both the pressure and the tension sides, osteoid tissue will form if the appliance is left out during the day. This osteoid is resistant to osteoblastic action and delay in reorganization is caused (Reitan 1969 [105]).

Salzmann 1966 [107] quotes Häupl (1954) as stating that the activator, by transmitting force through the alveolar process to the teeth, permits true "biologic" tooth movement. This biologic tooth movement is distinct from the "pathologic" tooth movement produced by orthodontic force.

Orthodontic Force.

This force usually is applied directly to the teeth

for the purpose of tooth movement in the alveolar process. Fixed or removable appliances may be used.

Salzmann 1966 [108] writes that from a biologic standpoint physiologic tooth movement cannot be produced through the use of orthodontic appliances. Pressure and Tension of varying degrees on the periodontal ligament initiate tooth movement through histologic bone resorption and deposition.

Graber 1972 [44] observes that orthodontics is a pathologic process from which the tissue recovers.

Reitan 1969 [104] states that the tissue reactions seen in physiologic and orthodontic tooth movement are not basically different. But the tissue changes caused by orthodontic tooth movement are more marked and extensive because the teeth are moved more rapidly during treatment. He continued that, even when using light orthodontic forces, except under carefully controlled experimental conditions, hyalinization of the periodontium is caused on the pressure side with resulting undermining resorption. He has referred [106] to forces of 30 gm. - 70 gm. applied as tipping forces and 80 gm. - 150 gm. applied to individual teeth for bodily movement, as light forces.

Orthopedic Force.

This force is applied with the intention of influencing the growth of facial bones.

Graber 1969 [43] has applied orthopedic force in the treatment of Class III, Class II, open-bite and closed-bite malformations. He states that the minimum force used must be above that which will move teeth, i.e. above 400 grams. He stresses that the force should be interrupted. The reason for this is two-fold:- (i) continuous force can cause damage to cementum and subjacent dentine. Interruption to the force allows recovery from the initiation of this osteoclastic activity. (ii) Continuous force is necessary to initiate tooth movement. Again, interruption allows a reversal of this unwanted cellular activity.

When discussing the intensity of force, Haas 1970 [49] states that optimal tooth movement occurs with relatively mild forces, either intermittent or continuous. They are usually directed towards a small area. At its source, an orthopedic force must be great because it is dissipated over a wide area, such as the maxillary suture, a complex of maxillary sutures or the mandible. At its focus of activity, however, the force is relatively light and physiologic in character. Orthodontic forces are measured in grams and orthopedic forces in kilograms. Orthopedic forces must be applied in the early growth period as the object is to promote or retard growth.

CONCLUSION.

Orthodontic research concerned with the response of bone to force has entered a new phase. Until ten years ago, the main emphasis was directed to finding the optimal rate of tooth movement and bone response, the optimal force required under varying circumstances and the optimal mechanical system to deliver the force. The results were observed clinically and histologically.

The findings of Storey were the principal achievements of this period, for, as well as defining the optimal forces and bone response, his work laid the foundation for the various light wire techniques which have evolved.

The systems for delivery of force to teeth and bone appear to have reached a peak in efficiency as regards application of force and resultant tooth movement and bone response.

Within the last decade the new phase of research has been directed towards discovering the biological mechanisms which control bone remodelling. This research is of great importance to orthodontics and I believe that further major advances in orthodontics must come from this region.

Most progress in this research has been achieved in the field of the piezoelectric mechanism of the response of bone to applied force. From the evidence presented by the various investigators, the simple piezoelectric theory propounded by Shamos and his colleagues appears to be valid. The successful use of this piezoelectric principle by the application of electric current to bone deficient areas with resultant bone stimulation in orthopedic cases has promise for a similar use in orthodontics. Possible fields are in cleft palate cases and where maxillary or mandibular repositioning is performed.

The work carried out by Bundy and his colleagues on thermal stimulation of bone response to orthodontic force has not been followed up by reports of further investigation. I think that this could be an area for future orthodontic research, with the reduction in treatment time as one aim.

If these mechanisms of bone change, when they are delineated, can be safely influenced by thermal, chemical, mechanical or electrical stimuli, then the rendering of orthodontic service could become a more exact and condensed procedure. The individual patient and the community should then gain further benefit.

APPENDIX I.

Piezoelectricity.

Piezoelectricity is defined by Cady 1964 [27] as "electric polarization produced by mechanical strain in crystals belonging to certain classes, the polarization being proportional to the strain and changing sign with it." This is the direct piezoelectric effect.

"The converse or reciprocal effect is that whereby a piezoelectric crystal becomes strained, when electrically polarized, by an amount proportional to the polarizing field."

Cady further states that if the pressure is replaced by tension (i.e. a reversal in the sign of the pressure), then the sign of the electric polarity becomes reversed also. He states that the pressure may be a shearing stress which is closely related to compression in its effects.

Cady explains that for a substance to exhibit piezoelectricity, it must have a structural "bias" or "one-wayness" which determines whether a given region on the surface shall show a positive or negative charge on compression. In the converse effect the same structural "bias" determines the sign of the deformation when an electric field is applied to the substance.

Shamos and Lavine 1964 [113] state that what determines whether or not a crystal is piezoelectric is its internal symmetry. If no combinations of stresses can alter the centre of gravity of its positive and negative charges then it is centrosymmetric and is not piezoelectric.

If an asymmetry of charge distribution occurs on application of stress, then the crystal is piezoelectric.

Anderson 1964 [1] states that the piezoelectric effect occurs only in insulating materials and is manifested on the surface of a di-electric crystal, subject to pressure, due to its internal lack of symmetry. Crystals may be divided into thirty-two classes on the basis of symmetry and of these, twenty are piezoelectric because of their low symmetry.

Bazhenov 1961 [10] draws attention to the work of A. V. Shubnikov in 1946 which demonstrated and confirmed the possibility of piezoelectricity in so called "textures". These textures are di-electrics which are not monocrystals but merely consist of separate crystal aggregates with oriented crystals having piezoelectric properties.

Collagen with the contained crystallites would be analogous to these textures.

Shields 1966 [119] writes that a major application of piezoelectricity is in transducers.

He defines a transducer "as any device that converts mechanical energy into a corresponding electrical signal. It may also work in the opposite direction, changing electrical to mechanical energy".

Shields divides piezoelectric transducers into two classifications where the piezoelectric element is used in the generator-action mode or where it is used in the motor-action mode. In the first case, when pressure is applied to the piezoelectric element a potential is developed. The amount of potential developed is dependent on the amount of pressure and the frequency of the applied pressure. In the second case a potential is applied to the piezoelectric element deforming it by an amount determined by the amplitude and frequency of the potential. The amount of developed voltage or pressure is dependent also on the physical size of the element.

The piezoelectric elements being considered in this treatise are the crystals of bone mineral and they are relatively small, averaging 200 Å in their greatest dimension (Termine 1972 [140]).

The composition of a piezoelectric bimorph has been described by Shields 1966[119]. The voltage produced by a piezoelectric element, when pressure is applied, is

extremely small but the voltage developed can be considerably increased for a given pressure by use of a piezoelectric bimorph. When two piezoelectric plates are connected together on their flat surfaces and a voltage is applied they deform in opposite directions, thus producing a bending, or twisting motion. Conversely, when they are bent they develop a potential that is greater than that produced by a single element of similar size.

Anderson 1964 [1] describes a piezoelectric bimorph arrangement of two piezoelectric elements bonded together, where voltage applied to one element causes an increase in length of that element but a lateral displacement of many times the longitudinal increase, with a consequent increased voltage in the second element.

Conversely, these bonded elements, being piezoelectric by nature, would generate an enhanced potential on deformation.

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