THE RESPONSE OF BONE TO ORTHODONTIC FORCE.

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PREFACE

Bone is a living cellular part of the animal organism. It is continually changing size and form and substance from the foetal period throughout the whole of life.

The response of this vital bone to force is a primary concern of the orthodontist.

Reitan 1969 [101] has written:-

> "The orthodontic methods of our time are more diversified than ever. The mechanics involved constitute one aspect of the problems, the biophysical principles the other, although both are closely linked. A few decades ago, histologic research was chiefly restricted to an examination of the tissue response elicited by special orthodontic methods already in use. The time has possibly come when it would be more logical to reverse this method of investigation, i.e., not take anything for granted, but instead construct or modify the appliances according to the principles revealed by the results of histologic and biomechanical investigations. Appliance construction and application would then be based less on an empirical approach, more on the knowledge of biophysical and biomechanical principles."

This treatise presents a short historical summary of early basic research on bone.

An outline of the cellular activity and growth of normal bone and its functions is then given as a necessary prelude to the discussion of applied orthodontic force.

Then the response of alveolar bone to orthodontic force is dealt with in detail.

Finally, various theories and investigations relative to the mechanism by which these changes are achieved are examined.

If these mechanisms were fully known and understood, the solution and rendering of our orthodontic treatment would be greatly facilitated, with corresponding benefit to the patient.

However, there has been no finality in the investigations into these mechanisms.

Storey 1972 [132] stated:-

> "Resorption of bone is associated with an increase in vascularity and the presence of osteoclasts at bone margins, but the precise stimulus which initiates the process is not known."

However, in the same address he said:-

> "If one accepts that bone is literally the foundation upon which dentistry and orthodontics rest, then it seems worth while to strive for complete understanding of the nature of bone as a tissue, as well as of how this tissue develops bones and how these function together as the skeleton."

HISTORICAL RESEARCH ON BONE.

A summary of the history of research into bone has been made by Enlow 1963 [34]. Some of the early discoveries pertinent to this discussion of orthodontic force on bone are presented.

Leeuwenhoek was one of the first to examine bone scientifically. In 1674 by means of early microscopes he discovered the canal system in bone. In 1691 Havers independently discovered the canals and the Haversian canals came to be called after him. Also, he was the first to state that bone was arranged on a lamellar basis. By the use of madder dye, Duhamel discovered in 1739-1743, that bone was formed by the periosteum. Hales in 1731 had shown that a long bone grows by an increase at its ends.

In 1798 John Hunter realised and stated the important proposition that bone grows by a process of outer deposition and inner resorption and "is constantly changing its matter." Goodsir, in 1845, discovered nucleated bodies within the lacunae of bone and that cells present on a bone surface become embedded in the newly deposited bone. Gegenbaur, in 1864, then showed that these particular cells are osteogenic and named them "osteoblasts".

Howship, in 1817, called notice to the eroded form of the surfaces of bone which are undergoing resorptive removal. Robin in 1864 first distinguished the osteoclast which name was bestowed on this cell type by Koelliker in 1872-73. Koelliker related the osteoclast, resorption and Howship's lacuna.

Monro, in 1763, commented on the shape of bones being such as to resist forces.

Hunter 1778 [56] discussed the alveolar processes and the fact that they tend to disappear when the teeth are lost and no functional force is then being transmitted to that particular section of alveolar process.

Ward in 1838, and Wynn in 1857, were the first to connect the pattern and arrangement of the cancellous trabeculae with forces acting on bone, some trabeculae being orientated for tension and some for compression. Culman and van Meyer in 1867 propounded that cancellous bone is arranged according to trajectories of stress (Enlow, 1963 [34]).

Wolff (1899) introduced his ideas summarized as "Wolff's Law" which relates the structure of a bone to the stresses and strains acting on it (Sissons, 1956 [121]).

Gebhardt in 1905, and Benninghoff in 1925, extended this concept of transformation as it applies to cancellous bone, to trabecula bone as well (Enlow, 1963 [34]).

However, Hunter [57] had, in 1778, recognised that bone will respond to applied force by reshaping and reforming.

AN OUTLINE OF THE NATURE AND CHEMISTRY OF BONE.

Bone provides the support for the soft tissues and major mechanical functions, and plays an important part in the biochemistry of the body. Vaughan 1970 [145] describes bone as being essentially of two types:-
(i) hard, compact, cortical bone found in the shafts of long bones surrounding marrow cavities and also forming the surfaces of all other bones, and (ii) spongy, cancellous or trabecular bone which is that bone contained between plates of compact bone.

Bone is a very vascular tissue (Vaughan 1970 [146]) and has a covering of periosteum, a fibrous membrane, which also has a rich blood supply (McLean and Urist 1968 [75]).

Haversian Bone.

Haversian bone is a type of compact bone present in the human skeleton, and is described by McLean and Urist 1968 [76]. It consists of secondary osteons which have formed by a process of remodelling of earlier bone tissue. Each osteon consists of a canal about 20 microns in diameter, lined by connective tissue cells, carrying a blood vessel for nutriment and surrounded by concentric layers of lamellarbone. Included in these layers are lacunae containing bone cells called osteocytes. These cells, in a Haversian system, communicate with each other through a system of canaliculi. Bone remodelling takes place on the surface of the Haversian canal. Other canals, called Volkmann's canals, are formed to carry blood vessels from the periosteum to the Haversian system. Vaughan 1970 [146] states that the Haversian canals are about 0.22 mm. apart. Hancox 1972 [51] has found that canaliculi from one system do not usually connect with another system, though he has demonstrated that they occasionally do.

Enlow 1966 [36] reviewing the types of bone commonly found in the developing and mature human, states that though the Haversian bone is considered to be the traditional type of compact bone, it is not the most common form of this bone.

The following brief reviews of bone types are taken from Enlow's report.

Primary Vascular Bone.

The most common type of bone found in the young growing human skeleton is non-Haversian in nature. This bone has a series of primary canals that anastomose in a longitudinal direction through the cortex. They are not surrounded by Haversian lamellae, nor have they undergone secondary remodelling. These canals are the chief type of vascular channel in human bone during the actively growing period following birth.

During active skeletal growth, Haversian systems replace primary canals only in certain specific locations such as muscle or tendon attachments.

Non-Vascular Bone.

Some areas of compact bone are completely non-vascular. This tissue usually forms when there is a relatively slow growth in an older individual. However, it can occur in any region where local growth has slowed in a younger person.

Non-Lamellar Bone.

This type of bone is formed extensively during periods of particularly rapid deposition of bone or in parts of a bone where local growth is rapid.

The fibrous matrix can be either "woven" or "Parallel-fibred", the latter being difficult to distinguish from true lamellar bone.

Coarse-Cancellous Bone.

This is a type of spongy bone and when present in the medulla is formed by endosteal deposition. It is not ordinarily formed by sub-periosteal deposition. The trabeculae of coarse-cancellous bone may have either a lamellar or non-lamellar matrix.

Fine-Cancellous Bone.

This bone is intermediate in texture between coarse-cancellous and compact cancellous bone and is widespread in the pre-natal skeleton. It also occurs in the growing post-natal skeleton in an area of bone where local growth is very rapid. This fine-cancellous bone is composed of non-lamellar tissue, either parallel-fibred or woven in nature. This formation of bone gives large quantities of new bone tissue in a short time. It can be of periosteal as well as endosteal origin.

Compacted Cancellous Bone.

During remodelling, the cortex can move in an endosteal direction. This movement involves a direct conversion of medullary coarse-cancellous bone into cortical compact bone. The inter-trabecular spaces are partially filled with new bone deposits until the cancellous marrow spaces are reduced to the diameter of ordinary vascular canals. The compact bone thus formed has a convoluted irregular structure due to the original trabeculae serving as templates for the new bone deposition.

This compacted cancellous bone is commonly seen in most routine histological bone examinations and comprises more than half of the bone tissue observed.

Fine cancellous bone may also be compacted. In the post-natal skeleton it undergoes compaction soon after formation by new bone being added within each cancelli. Cylinders of either lamellar or parallel-fibred bone are laid down in the tubular cancellous spaces producing a primary osteon. These are distinguished from the Haversian osteon by (i) not resulting from secondary remodelling processes and (ii) not being surrounded by an encircling resorption cement line.

Cortical bone composed of these primary osteons are found in age levels involving fast skeletal growth and are thus present in the very young human skeleton.

Inner and Outer Circumferential Bone.

When lamellar bone is deposited on the endosteal or periosteal surfaces, it follows the contour of the existing older surface. On the endosteal surface, the new lamellar bone follows the surface of the trabeculae or, if the trabeculae are widely spaced, uninterrupted sheets of circumferential lamella are laid down. Sub-Periosteal layers of outer circumferential lamellar bone result if the periosteal surface is relatively smooth. Inner or outer circumferential layers may be vascular or non-vascular. Haversian systems of secondary osteons do not form in zones of periosteal lamellar bone. The area must undergo remodelling processes of resorption and secondary redeposition for the production of Haversian systems.

Prior to skeletal maturity in the early twenties in man, most periosteal zones of the cortex have a large amount of non-Haversian bone, except at points of muscle attachment. After maturity, Haversian reconstruction of the cortical bone continues until, in extreme old age, most of the endosteal and periosteal zones have been replaced.

However, Haversian systems are common within the endosteal zones of the cortex of the young growing skeleton.

Hancox 1972 [51] states that beneath the periosteum there is an outer zone of very dense circumferential lamellae wrapped around the bone. Deeper, there are concentric lamellae arranged around Haversian canals. He reports that in cancellous bone in the medullary region, the trabeculae are built of lamellae running more or less parallel.

Smith 1960 [123] reports that surface bone forms on the periosteal and endosteal aspects of long bones in the form of thin layers of parallel-fibred bone. In some bones this layer may be of such thickness that it comprises the greater part of the width of the bone. He further states that when surface bone is formed in a region not previously ossified, Sharpey fibres are frequently included within it. He accepts that Sharpey fibres represent originally extra-osseus collagen bundles which have been included within the bone during its growth.

Smith's findings agree with Enlow's review concerning the type of tissue in developing bone. Smith states that the type of bone formed beneath the periosteum during growth always consists of either woven-fibred bone or surface bone. After this has been formed, two changes occur, (i) the vascular spaces in woven-fibred bone become filled by primary osteons soon after the tissue is formed, and (ii) secondary osteons are formed in regions occupied by surface bone or by woven-fibred bone and primary osteons. The formation of secondary osteons usually begins before growth is complete, and the process continues at varying rates until death.

Smith states that bone undergoes two processes, (i) growth, involving production of woven-fibred bone and surface bone, and (ii) alteration to the internal architecture of bone, involving the formation of primary and secondary osteons.

Reitan 1969 [102] states cancellous bone is more abundant in the bones of young persons. The activity of resorption is facilitated by the number of resorption cells which increases according to the number of marrow spaces. Therefore the anatomical structure of the bone of young persons is ideal for orthodontic movement.

Composition of Bone.

Bone is composed of a cellular matrix surrounded by a ground substance consisting mostly of mucopolysaccharides through which there is a structure of collagen fibres. The hardness of bone is due to the deposition within the soft matrix of a complex mineral substance composed largely of calcium salts, phosphate, carbonate and citrate (McLean and Urist 1968 [72]).

Bone collagen is made up of fibrils and has a crystalline structure (McLean and Urist 1968 [77]). This collagen is formed by osteoblasts (Cameron, et al. 1964 [28]).

Neuman and Neuman 1958 [87] examined and compared the crystals of bone collagen and apatite and found a very close similarity between the structures of these two crystals. They suggested that by a process of epitaxy, the collagen crystals contribute to the mineralization mechanism of bone.

The water content of bone varies with the species of animal, its age and the nature of the particular bone. As an example, the water content of compact bone of the adult dog is about 3.7% by weight (McLean and Urist 1968 [78]). The water in bone is the medium for cell nutrition and transport of inorganic ions. When crystallization of new bone occurs the organic content remains constant in volume and it is the water which is displaced by the newly formed crystals. The ability for ions to diffuse slowly between the crystals so formed is retained, however (McLean and

Urist 1968 [78]).

Bone Cells and Modulation.

There are three main cellular elements concerned with bone - osteoblasts, osteocytes and osteoclasts.

These bone cells are formed by modulation from a spindle-shaped osteo-progenitor type of connective tissue cell in the periosteum (Cameron, et al. 1964 [28]).

Vaughan quotes Young, 1962 [152] who suggests that the term "modulation" instead of "differentiation" should be applied to bone cells because of their ability to change their activity according to micro-environmental conditions. Differentiation implies a permanent specialization.

Modulation from the osteo-progenitor cell results in a cessation of the function of mitosis and on return to the osteo-progenitor condition this ability is regained.

Osteoblasts.

The bone-forming cells are osteoblasts and, when active, osteoblasts are usually one layer thick. They are columnar cells with a single nucleus at the end farthest from the bone surface. Osteoblasts lay down bone matrix, forming both ground substance and collagen (Vaughan 1970 [148]). Fitton-Jackson in 1960, during electron microscope experiments, reported collagen fibres adjacent to and also merging with the surface of the osteoblast, (Vaughan 1970 [147]).

There is evidence of an amorphous non-crystalline calcium phosphate structure as well as a calcium phosphate apatite crystal structure in the mineralized material of bone (Vaughan 1970 [153]).

The first mineral formed in the bone is this non-crystalline amorphous calcium phosphate. There is no direct transformation of amorphous calcium phosphate to the crystalline mineral. The amorphous form must be dissolved and its constituent ions be redeposited in crystalline form (McLean and Urist 1968 [80]).

In 1973 Eanes, et al. [33] reported in vitro experiments where amorphous calcium phosphate was formed in solution in spheroidal and discoid form. Calcium apatite crystals then appeared on the surface of the amorphous calcium phosphate spherules and discs. They stated that the crystalline form of calcium phosphate did not fill the space previously occupied by the spherules. A solid state conversion to the crystalline form does not take place but the transformation is achieved by solution and redeposition.

Mineralization of apatite occurs by deposition of a crystal seed in the collagen fibril of bone, not by precipitation of tissue fluid oversaturated with calcium or phosphate ions (Vaughan 1970 [154], and Luben, et al. 1973 [67]).

The mechanism by which the osteoblast accomplishes this mineralization is not known.

Vaughan 1970 [155] reports that De Luca has suggested that Vitamin D acts by facilitating the transport of calcium from bone fluid into bone cells.

Brown 1968 [23] refers to Becker, et al., who in 1964 proposed that Vitamin D may act as an impurity in the apatite-collagen lattice and enhance the bioelectrical effect.

Oxidative enzyme activity has been observed in relation to osteoblastic activity and this is thought to be part of the mechanism (Deguchi and Mori 1968 [32]). They reported that during their histochemical experiments numerous osteoblasts on the alveolar septa of bone in the formative phase showed a fairly intense activity of lactate, malate, isocitrate and glucose - 6 - phosphate dehydrogenases and a moderate activity of succinate dehydrogenase.

Takahashi 1972 [138] observed alkaline phosphatase on the osteoblastic cell membrane and acid phosphatase in the Golgi apparatus of the cell during electron microscopic studies of osteogenic cells in the alveolar bone of rats. He reported observing three different types of osteocytes during these studies. They were probably osteocytes in three different stages of modulation.

Osteocytes.

The osteocytes are cells which have many fine branching processes and are situated in lacunae in the bone substance. They are formed from osteoblasts which have been surrounded by deposited mineralized tissue. These cells are concerned with the continuous exchange of both mineral and organic components between blood and matrix (Vaughan 1970 [149]). It is thought that they play a part in the regulation of the calcium concentration in the body fluids (McLean and Urist 1968 [73]). Osteocytes cannot regenerate by mitosis and as they die they are removed by macrophages in the calcified matrix, and new bone is built by new osteoblasts (Linkow 1970 [66]).

Osteoclasts.

It is generally accepted that the osteoclast is the cell which resorbs bone (McLean and Urist 1968 [74]). This cell is relatively large and multinucleated, containing from 2 - 100 nuclei. The most notable microscopic feature is its ruffled brush border in the zone adjacent to bone. Viewed under a light microscope this border appears like the hairs of a fine brush. Using the electron microscope it is found to consist of a cytoplasmic system of channels running towards the interior of the cell from the resorbing bone surface. These channels are formed by deep folds in the cell membrane

(Vaughan 1970 [150]). Osteoclasts contain many vacuoles, a large number of which are close to the brush border and apatite crystals may be seen in some of these vacuoles undergoing resorption (McLean and Urist 1968 [74]).

Hancox 1956 [50] refers to the short life of the osteoclasts. They appear in response to stimulus, absorb bone, and disappear again in the space of 48 hours.

Trueta 1963 [141] claims that the osteoclast is only accidently present during bone resorption as a result of the fusing of osteocytes and osteoblasts into multinucleated cells which were left unsupported by the removal of rigid structures around them. He theorises that a vascular mechanism is responsible for the resorption. This theory will be discussed later.

Johnson 1964 [59] believes that active hyperaemia, due to high oxygen tension, induces osteoclastic activity, and Bassett 1965 [4] speculates that the increased vascularity could provide more electron "sinks", through streaming potentials, and thus cause bone resorption by conducting electrons away.

Deguchi and Mori 1968 [32] reported that osteoclasts showed a strong activity of succinate, lactate and malate dehydrogenases and a moderate activity of isocitrate and glucose - 6 - phosphate dehydrogenases during their histochemical observations of oxidative enzymes during experimental tooth movement.

Vaes 1968 [143] reported that bone resorption of both the mineral and organic components of the osseous matrix was obtained in tissue culture by the action of parathyroid hormone. Six lysosomal acid hydrolases were excreted from osteoclasts without rupture of the cell membrane. He presumed that this was the result of an exocytosis of the lysosomal content of the cells which involved mechanisms similar to those controlling secretion of this content into the digestive vacuoles.

Acid was also released, more lactate than citrate being detected.

Vaes theorised that the acid hydrolases of the lysosomes resorb the organic matrix of bone and that acid dissolves the bone mineral.

He stated that no precise mechanism could be proposed to explain the exocytosis and the exact action of the parathyroid hormone.

Growth and reshaping of bone occurs through a simultaneous process of deposition and resorption of bone. When bone is being formed it passes through three stages. Firstly, osteoid is formed by the osteoblast. This osteoid is not mineralized when first laid down and is not able to be resorbed by osteoclasts. It soon mineralizes and becomes bundle bone and finally the bundle bone is transformed into lamellated bone.

The lamina dura lining the root socket of the alveolar process may appear on an x-ray as a white line thicker than normal due to this increased mineralization during growth or orthodontic movement (Reitan 1969 [103]).

However, Black 1965 [20] states that the radiographic image of the lamina dura may be accentuated by what is known as the "Eberhard effect". This can occur during the process of developing films and can place a halo effect at the junction of light and dark objects.

New bone is added to one face of a bone and old bone resorbed on the other side, giving a movement or increase in size in one direction. If this process then takes place on an opposite area of the same bone the net result will be a total increase in the dimension of the bone. The process of reshaping by this means is termed "drift" (Enlow 1963 [35]).

Mineral Equilibrium.

Termine 1972 [139] states that because bone mineral is an inorganic substance which lends rigidity and hardness to the skeleton, there is a natural tendency to consider that it is an almost inert material. However, it is the mineral portion of the skeleton which is involved in maintaining mineral metabolism and homeostasis. As no comparable physiological function is attributed to the organic matrix of bone, therefore the mineral is the most active part of all the structural constituents of bone.

The bone serves as a store for the minerals in the body especially calcium and phosphorus (McLean and Urist 1968 [84]). A balance is held between calcium and phosphorus in the mineral phase as well as in solution in the body fluids (McLean and Urist 1968 [83]).

The maintenance of this equilibrium is assisted by the relatively enormous aggregate area of the bone crystal surfaces which are bathed in a few litres of body fluid. This area in a 70 kg. man is estimated to be about 40.5 hectares (McLean and Urist 1968 [79]). The surfaces of the crystals are in equilibrium with the fluid of their environment and are subject to constant ion exchange. This is a vital dynamic system and the chemistry of the surface is different from that of the interior of the crystal (McLean and Urist 1968 [81]).

Mineral Storage.

Magnesium is an example of an element held in storage in bone. Up to one-third of the skeletal store of magnesium is available for mobilization in case of magnesium deficiency (McLean and Urist 1968 [85], Nielsen 1973 [88]). Magnesium is also necessary for the solubility mechanism of calcium. Deficiency of magnesium impairs the response of bone to parathyroid hormone (Nielsen 1973 [88]).

Bone Remodelling

In addition to the changes in bone incident to growth, there is continuous internal remodelling throughout the life of the individual (McLean and Urist 1968 [76]). This is caused by constant osteoclastic and osteoblastic activity. McLean and Urist 1968 [76] reporting Frost, et al. 1960, state that the turn-over rate of bone for a 57 year old male was 0.036% by weight for femur and fibula, and 0.012% for the tibia per day.

Johnson 1964 [59] wrote of the importance of the rates of skeletal change to an understanding of bone physiology. The resorption cavity forms rapidly and fills slowly and both the rates are more rapid in the young person. He stated that an osteoclast resorbs 200,000 cubic microns of bone in one day and an osteoblast forms 1,200 cubic microns of bone in ten days (Johnson 1964 [61]). Also, he wrote that a ratio of osteoblasts to osteoclasts of 150 : 1 is indicated for balanced activity (Johnson 1964 [60]).

The evidence that bone formation is usually a slower process than bone removal has been supported by Geiser and Trueta 1958 [39].

Growth Spurt.

If a widespread remodelling occurs in a short period of time at any age, a temporary porosis will result due to this disparity in rates. This happens in adolescent growth spurts. With adolescent boys, where the muscle strength per volume increases, this porosis can be the cause of non-rheumatic "growing pains" (Johnson 1964 [59]).

The growth spurt begins on an average between 10½ to 12 years of age for girls and between the ages of 12 and 17 years for boys (Graber 1972 [45]).

The mean length of the growth spurt is approximately 2½ years in the male (Bergerson 1972 [18]) and about 2 years in girls (Grave 1973 [46]).

Methods of predicting the beginning of the growth spurt as it affects facial development have been investigated. The appearance of the ossification of the ulnar metacarpophalangeal sesamoid of the thumb has been observed to coincide with the commencement of this spurt (Chapman 1972 [29], Grave 1973 [47]).

Chapman 1972 [29] also states that the duration of the adolescent spurt coincides with the duration of the development of the sesamoid.

Grave 1973 [47] also related the ossification of the pisiform bone in girls and the hamate bone in boys to commencement of the growth spurt.

Pileski, Woodside and James 1973 [100], in a sample of 91 males and 108 females, observed the mandibular growth. They stated that, for 74.7% of males and 78.7% of females, if the ulnar sesamoid bone is not visible on a radiograph, then maximum acceleration of mandibular growth is still to come. However, they further stated that 25.3% of males and 19.5% of females did not show appearance of the ulnar sesamoid bone until after maximum velocity of mandibular growth was completed.

They conclude that though appearance of the sesamoid bone is accepted as an indicator of the growth spurt being imminent, the correlations of their statistics are too low for any possible clinical prediction of maximum mandibular growth velocity at adolescence.

Perry 1972 [98] points out the usefulness of the hand-wrist radiograph as an indicator of the growth spurt but states that cephalometric radiographs must be taken to determine the direction of growth in addition to its intensity.

He listed four categories of growth expectation:- Category A, where extraction or non-extraction treatment will apparently be successful because of the favourable forward and downward growth of the mandible at a satisfactory rate. Category B, where the direction of growth is satisfactory but the rate is too great or too small. Category C, where the direction of growth is unfavourable but the rate is satisfactory. Category D, where the direction and rate of growth are both unfavourable.

As well as the timing, the direction and rate of growth must influence the application of orthodontic force.

The growth spurt is of prime interest to the orthodontist as regards timing of the application of force, because of the resulting relative ease of tooth movement.

The Alveolar Process

The alveolar processes are the bones which are of principal concern to the orthodontist. The following description is taken from Orban 1972 [96].

These alveolar processes are the parts of the maxilla and mandible which support the sockets of the teeth. There are two parts of the alveolar process, a thin plate of bone that surrounds the root and the tooth and has the periodontal ligament attached to it. This is the alveolar bone proper. The second part is that bone, called supporting alveolar bone, which encases the alveolar bone. It is also of two parts:- (a) cortical bone forming the buccolabial and lingual plates of the alveolar process, and (b) spongy bone between these plates and the alveolar bone proper.

The cortical plates are continuous with those of the maxilla and mandible. They are thinnest in the maxilla and thickest in the buccal pre-molar / molar region of the mandible. In the maxilla the outer cortical plate is perforated by many small openings through which pass lymph and blood vessels. In the mandible the cortical bone is dense. The anterior section of the supporting bone in both jaws is very thin and there is no spongy bone here, the cortical plate being fused with the alveolar bone proper.

Canals of Zuckerhandle and Hirschfeld pass through the inter-radicular septa and contain the inter-radicular blood vessels and nerves.

The cortical plates have longitudinal lamellae and Haversian systems. The spongy bone can be classified into two types:- (i) where the trabeculae are arranged in a regular and horizontal manner more commonly seen in the mandible, and (ii) where the trabeculae are irregular, more common in the maxilla. Both have varied thickness of trabeculae and size of marrow spaces. The marrow spaces in the alveolar process may contain haemopoietic marrow but usually has fatty marrow.

The alveolar bone proper is perforated by many openings which carry blood vessels and nerves into the periodontal ligament and is called the cribriform plate or lamina dura. This alveolar bone proper is composed partly of lamellated and partly of bundle bone. Some lamellae are roughly parallel to the adjacent marrow spaces and others form Haversian systems. Bundle bone is that bone in which the fibres of the periodontal ligament are anchored. The bundles of principal fibres continue in the bone as Sharpey fibres. The fibrils in the intercellular-substance of the bundle bone are relatively few and are arranged at right angles to the Sharpey fibres.

The bone of the alveolar process is similar to bone elsewhere in the body. It is continually active through apposition and resorption of bone in response to functional and systemic demands.

The response of bone to orthodontic force is superimposed on this normal activity.

Vitamin A.

Vitamin A is necessary for the maintenance of bone. In growing bone, Vitamin A is essential for the function of epiphyseal cartilage cells and thus influences normal growth, maturation and remodelling processes (McLean and Urist 1968 [82]).

Vitamin A also supports osteoclastic action. Vaughan 1970 [156], reporting Reynolds (1968), states that Vitamin A causes bone resorption by stimulating cellular release of hydrolytic enzymes. Calcitonin, secreted by the thyroid glands, acts as a balance for the Vitamin A by inhibiting the release of mineral and also, Reynolds suggests, by inhibiting the breakdown of mature collagen by osteoclasts.

Hypovitaminosis A in man is very rare and little is known of its effect. During animal experiments there has been recorded a thickening of bones in the face of dogs, (Barnicot and Datta 1956 [3].)

Excess dosage of Vitamin A is toxic and leads to fragility and fractures of long bones. Routine prophylactic feeding of Vitamin A concentrate to healthy young children can be a hazard in this respect (McLean and Urist 1968 [82]).

A connection between Vitamin A metabolism and trace zinc in the diet has been proposed by Smith, et al., 1973 [122].

They state that cirrhotic patients have depressed zinc concentrations in plasma and concomitant depression of Vitamin A concentration in plasma.

Experiments conducted on rats demonstrated that zinc therapy resulted in Vitamin A being mobilized from the liver into plasma and suggested that zinc is necessary for maintaining normal concentrations of plasma Vitamin A.

Vitamin C.

Vitamin C is concerned with the formation and maintenance of intercellular material and in bone is concerned mainly with collagen synthesis. When a deficiency of Vitamin C occurs, deposition of the intercellular matrix ceases and osteoblasts assume the form of reticular cells. The calcification mechanism is not affected but abnormal connective tissue formed in the bone is not calcifiable. This condition is reversible when ascorbic acid is supplied (McLean and Urist 1968 [82]).

Vaughan 1970 [157] states that in growing children with ascorbic acid deficiency the main changes from normal function in bone, are seen in the epiphysis. The cartilage cells continue to multiply in columns and the matrix calcifies and forms a fragile brittle network which breaks. Osteoid formation may cease and osteoblasts are diminished in number, with connective tissue fibroblasts predominating. Osteoclasts are not affected to any extent. There may be sub-periosteal haemorrhage.

There does not appear to be any ill effect from ingestion of excessive amounts of ascorbic acid.

Vitamin D and Parathyroid Hormone (PTH).

Vitamin D and Parathyroid Hormone (PTH) are concerned with the metabolism of Calcium and Phosphorous and the bone/plasma/intercellular fluid Calcium ion balance.

This outline of the system is taken from McLean and Urist 1968 [83].

Vitamin D and PTH are regarded as parts of an integrated system which controls the mechanisms pertaining to Calcium/Phosphate mineral balance. However, the Vitamin D and PTH do not influence each other. The parathyroid glands control the Calcium ion concentration in the plasma, mainly by organizing the exchange of Calcium from the skeleton. They also control excretion of phosphate by the kidneys and aid absorption of Calcium in the gastrointestinal tract. Vitamin D is the main influence on absorption of Calcium. It also has an effect on the mobilization of mineral from bone, complementing the parathyroids in this field.

Both Vitamin D and PTH help the formation of citrate in bone.

Vitamin D exerts its main effect by influencing the intestinal absorption of Calcium. A deficiency of Vitamin D results in the appearance of rickets. The basis of this condition is the formation of an uncalcifiable matrix in bone and the resultant poor overall calcification. A large over-supply of Vitamin D results in marked resorption of bone.

The PTH regulates the Calcium ion concentration in blood by acting on the skeleton. Regulation of the Calcium plasma level is also aided by the effect of the hormone on tubular re-absorption of phosphate by the kidneys.

The cellular and sub-cellular mechanism by which the PTH acts on bone is not known. The exchange of the Calcium ions from bone to blood is extremely rapid, as much as 100% per minute in young animals and up to 25% in adult man. The parathyroids control this activity. The Calcium ion concentration in the blood is the stimulus to which the parathyroids respond and thus the mechanism becomes a negative feed-back system.

The extra-cellular fluid also acts as a buffer to the blood and it is the first to be depleted of Calcium ions if they are needed in the blood. There is also a dual system of exchange at the bone. The ions on the surface of the bone are in equilibrium with the ions in the fluid in contact with them. They can readily exchange. The osteoclasts which are in contact with the bone can also act, but more slowly.

At the sub-cellular level, Vitamin D, whether given in vivo or in vitro stimulates the release of Calcium Phosphate from mitochondria. If PTH is added in vitro, a synergistic action is set up with Vitamin D. In animal experiments using rats the hormone also stimulated the release of Calcium but only in those rats receiving Vitamin D. Without Vitamin D, it has no effect. Therefore, Vitamin D and PTH appear to be component parts of an integrated mineral control system in the organism.

Calcitonin.

Martin 1973 [68] has written of the origin of calcitonin and its role in the mechanism which maintains the Calcium ion balance. The source of calcitonin is the thyroid gland. It has been established that calcitonin acts directly on bone in organ culture to inhibit its resorption. It inhibits the movement of Calcium from bone rather than aiding its deposition.

The excretion of urinary hydroxyproline in rats is inhibited by calcitonin. Urinary hydroxyproline excretion is a result of the breakdown of bone collagen and it indirectly points to the amount of bone resorption.

The effect of calcitonin is greater in younger animals because of the more rapid resorption rate in growing bone. In an adult, large doses of calcitonin do not lower Calcium whereas a hypocalcaemic effect from the doses of the hormone is always seen in children.

Martin refers to Cochran, et al. who, in 1969, stated that bone resorption makes little contribution to the maintenance of serum Calcium in adults, but that this balance is determined by the relation between the rate of Calcium absorption and the renal threshold for Calcium. The latter is determined by PTH and perhaps to some extent by calcitonin.

Martin states that if calcitonin is important in Calcium homeostosis, it may only be so in young animals in which the bone resorption rate is high.

There has been no finality in this field of research on vitamins and hormones and their effect on bone. The effect of applied orthodontic force is in this same field of bone deposition and resorption, especially where it concerns the growing individual. Some method of facilitating orthodontic movement may evolve from further research on the action of these vitamins and hormones.

SOME ASPECTS OF BONE REACTION TO APPLIED ORTHODONTIC FORCE.

Tooth Bending.

As orthodontic force is applied to a tooth the first reaction is within the tooth itself, when it bends slightly.

Hixon, et al. 1970 [53] stated that "the magnitude of this tooth bending is too small to be of either clinical of theoretical significance to our study." However, future investigations may attach more value to this phenomenon especially in regard to the piezoelectric effect. (See page 111).

Bone Bending.

When the orthodontic force is transmitted by the periodontal ligament to the alveolar wall, the wall itself bends.

Muhlemann and Zander [71] in 1954 experimented on monkeys and found that one of the components of initial tooth movement is bending of the alveolar wall. They applied force to the lingual surface of the crown of an upper cuspid tooth. The bone movement at the labial alveolar margin was 0.035 mm. with a force of 300 gms. applied. This bone deformation is reversible with removal of the load.

Muhlemann and Zander divided the total tooth movement under horizontal force into three components: (i) the initial tooth movement in the socket, (ii) the bending of the alveolar bone, and (iii) the tissue compression.

Muhlemann 1960 [70] states that for applied forces of 500 gms, tooth mobility is greater in children and young adults. It is slightly greater in females and increases in pregnancy. It fluctuates during a 24 hour period, and is lowest in the evening and highest in the morning just after awakening.

In further investigations on a group of children aged 7 to 15 years, the influence of artificially induced occlusal trauma on tooth mobility was studied by Muhlemann 1954 [69]. He stated that a definition of occlusal trauma was impossible but considered that the measurement of tooth mobility, after forces were applied by a variety of orthodontic means and then removed, would contribute to an understanding of "occlusal trauma". Results were given for those cases where the force applied exceeded 500 gms. and in all instances the tooth mobility was increased.

In the case of the functional appliances used, i.e. inclined planes and oral screens, an increase of functional forces influencing the teeth was always accompanied by an increase in tooth mobility. Decrease in function to within normal limits was associated with a decrease of tooth mobility.

Muhlemann did not specify a measurement applying to the bone deformation in these instances. It is not known, therefore, if the increase or decrease in tooth mobility noted was partly due to increased or decreased bone deformation.

O'Leary, et al. 1966 [92] conducted mobility tests on a group of adults over 24 hour periods. Their results were in general agreement with those of Muhlemann in that they found lack of contact and function caused an increase in tooth mobility.

Investigations on the behaviour of the alveolar bone, when a tooth was subjected to applied force, were carried out by Picton in 1965 [99]. He used monkeys as his subjects.

Horizontal force of up to 1 kg. was applied over 5 secs., in thrusts at intervals of 10 secs. Displacement of bone was observed at or below 50 gms. force in more than 36% of records and under 100 gms. in 72%. Labial alveolar bone moved with a force below 100 gms. in 77% of records compared with 66% of records for lingual bone. The labial plate under both compression and tension was moved a greater distance than the lingual plate. The bone on the compression side was moved by low force a similar number of times to that on the tension side. The labial plate was moved a greater distance than the lingual plate under both compression and tension forces. The displacement distances for compression and tension were the same for both plates of bone. There was linear displacement and recoil of the socket under tension and compression.

Intrusive thrusts caused dilation of the socket in 80% of records. In more than half of the records displacement occurred with a force of less than 100 gms. With 1 kg. force the labial plate was displaced an average 7.6 µ and the lingual plate 4.4 µ. The adjacent sockets also became dilated by the same amount when axial loads were applied.

The movement of teeth was in two phases, a free phase at first, and a second more gradual linear phase.

In a number of records the horizontal displacement of bone was opposite to the force. Picton explained this by stating that in these cases the force may have an intrusive component which would cause dilation of the socket and produce this opposite effect.

Picton noted that with forces in excess of 100 gms, the movement of the tooth often exceeded the movement of the bone. He drew attention to Muhlemann and Zaner's 1954 [71] experiments and their conclusion that tissue compression was a factor in tooth movement after the first phase of relatively free movement. Picton stated that both sides of the periodontal tissue must be considered. As his findings showed that the tooth moved further than the alveolar border on both the compression and tension sides and that these plates are displaced the same distance, he concluded that cells and/or fluid are displaced from the compression side and may move to the tension side.

He theorised that his findings on tooth movement indicated a gradual transition from a phase of fluid or cell displacement to a phase of bone displacement combined with soft tissue movements in the periodontal membrane. The fluid in the compressed side could move to fill the volume created on the tension side or be extruded from the walls of the socket.

The tooth recoils a considerable distance in a linear manner when the force is removed. Picton hypothesised that this is probably due to the elastic recoil of the socket and of the displaced connective tissue with a final phase due to the return of fluid to the membrane.

Grimm [48] in 1972 investigated the amount of bending of the interalveolar septum between the canine and first premolar tooth on two 12-year old patients and on a fresh 48-year old cadaver.

Access for the insertion of the probes of the gauges was obtained by extraction of the first premolar tooth.

The bending of the bone was measured at the alveolar crest. The bone response in all cases was unexpected in that a negative reaction was first recorded when force was applied to the tooth. When a force of 500 gms. was applied to the canine, there was initial negative movement of the bone at the alveolar crest amounting to 15 - 25 microns opposite to the applied force. This negative movement reversed after about 1 minute.

When the force was removed the tooth and bone rebounded and overbounded. Then the bone slowly warped in the opposite direction and settled back to the zero position.

When force was applied to accentuate this overbounding reaction, the negative bone response occurred again to an average of 15 microns. The final positive bending of the bone was 20 - 25 microns with 1000 - 1500 grams of force applied to the tooth.

Grimm offered two hypotheses to possibly explain the initial negative movement of the bone.

The first was that the advancing tooth stretched the septal bone on the pressure side which thinned it, then created tension strains and caused it to bend back towards the advancing tooth. The septal wall, pulled by the periodontal ligament caused compressive strains which thickened the wall and caused it to bend away from the moving tooth.

The second hypothesis was that the tipping tooth pushed the septal wall on the tension side at the apical section and deflected the whole wall, up to the alveolar crest, away from the tooth. Grimm does not explain how this hypothesis would fit the "pressure" side of the tooth.

The explanation for these results obtained by Grimm may be the same as that offered by Picton, i.e. an intrusive component in the applied force acted and caused socket dilation.

These findings of bone displacement, as the result of force applied to teeth, support the piezoelectric theory of bone remodelling in response to orthodontic force.

Threshold Levels of Force Necessary for Tooth Movement.

The minimum force necessary to cause tooth movement has been investigated by Lear, et al.[65] in 1972. The force duration and frequency were also examined as the object was to study the link between transient muscle movements and tooth movement.

Firstly, lingual and buccal muscle forces were investigated and measured. It was found that forces up to 35 gms. could develop during mastication and speech, and resting buccolingual forces of 1 gm. occurred. The duration varied from 25 m.secs. to a considerable period when the musculature was at rest.

Five adult males were subjects for the experiments and the force was applied by an electric solenoid apparatus to premolars. Forces varying from 6.3 gms. to 0.5 gms. were applied for periods varying from 100 m.secs. to 25 m.secs.

The results indicated that forces as low as 1.6 - 2.5 gms. applied for 25 m.secs. displaced premolar teeth.

The conclusion was that the activities of the buccal and lingual musculature were capable of moving teeth. However, it was stated that it had not been established whether such small deflections could have an osteogenic effect, nor was the mechanism known by which a change in osteogenic balance could be triggered. But owing to the lever action of tipping movement of teeth, a small displacement could cause a significant concentration of force per unit area and thus initiate bone responses to these small forces.

Effect of Compressive Force on Cells.

One aspect of orthodontic force, namely the effects of compressive forces on cells, was investigated by Nakamura and Thonard 1972 [86].

They applied nominal forces of 40 grams/cm.^{2}, 20 grams/cm.^{2}, and 10 grams/cm.^{2} for periods up to four hours on mouse fibroblast cells, but only about 75% of the force was exerted on the cells. This was thought to be due to the use of an elastic acetate membrane instead of glass to apply the force to the cells. This membrane was used to permit the necessary gas exchange and nutrient supply of normal cell metabolism to take place.

Previous studies had reported cell necrosis at a force of 26.94 grams/cm.^{2} but it is now thought that this result was due in part to the glass force-transmitting device inhibiting normal cell metabolism.

There were no significant changes noted by autoradiographic procedures in the cells subjected to approximately 30 grams/cm.^{2}. Nakamura and Thonard state that these results indicate that protein synthesis, which is vital to the maintenance of life, will be maintained by the majority of cells subjected to forces up to 30 grams/cm.^{2} for a maximum period of four hours.

OPTIMAL BONE RESPONSE RELATED TO ORTHODONTIC FORCE.

The teeth are sustained in position by a dynamic equilibrium of forces. These forces range from a few grams (pressure from the cheek), to several kilograms (maticatory force), their directions are variable, and the time of application is from fractions of a second to some hours (Hotz 1961 [54]).

Orthodontic force is artificially introduced into this system to produce a resultant force which will move a tooth or teeth to a new position.

Research up to 1952.

The first histological examination of the results of applied orthodontic force was made by Sandstedt in 1904, during experiments on a dog (Schwarz 1932 [109]). During these studies he discovered the process of undermining resorption. He found that both strong and weak forces moved teeth and he also fixed the centre of rotation of a tipped single rooted tooth at about one-third the length of the root from the apex.

Oppenheim followed in 1910 with experiments on a baboon. His histological interpretations were incorrect in some instances and he fixed the centre of rotation at the apex of the root of a tipped single rooted tooth. He missed the point of undermining resorption being due to strong forces (Schwarz 1932 [110]).

In 1932 Schwarz [111] published the results of experiments on a dog. He theorised that a force below that of the capillary blood pressure was the ideal orthodontic force from a biological standpoint. He formulated "The four degrees of biologic effect caused by orthodontic forces." Summarised, they are:-

1st Degree Force: the force so short in duration or so slight there is no reaction to supporting tissues.

2nd Degree Force: the force is gentle and below the pressure in blood capillaries, i.e. less than 20-26 gms/sq.cm, but intensive enough to cause "lively" resorption of alveolar bone. No resorption of the root is caused.

3rd Degree Force: the force is fairly strong. It just represses the flow in the blood capillaries in the region of pressure. The periodontium is deprived of blood and necrosis occurs. Resorption of bone occurs around the margins of this necrosis. Also root resorption can occur. 4th Degree Force: the force is strong enough for the tooth to crush the supporting tissues and to touch the bone of the alveolar socket. Necrosis occurs together with the possibility of pulp death. Resorption occurs around the necrotic areas and undermining resorption of these areas also occurs from the marrow spaces.

The figures which Schwarz gave as the optimal force, i.e. 20-26 gms/sq.cm. were queried by Smith and Storey 1952 [124], Storey 1953 [126], and Bien 1966 [19]. Storey drew attention to the fact that (i) the force was a tipping one and the pressure on the periodontal membrane would vary from apex to gingival margin, and (ii) the effect of the periodontal membrane on the tension side was ignored.

Bien maintained that this theory of Schwarz was in apparent contradiction to the fact that biting forces of approximately 1500 gms/sq.cm. do not crush the periodontal membrane or impact the tooth through the bone.

Herzberg [52] in 1932 carried out the first experiments concerned with the results of orthodontic force on a human subject. He found that the histological results closely paralleled those of Oppenheim on animals.

In 1937 Stuteville [135] wrote of experiments on humans and dogs and maintained that the movement of teeth in occlusion is more traumatic than the movement of those teeth which are free of occlusal interference. Also that the amount of space through which the force is active and not the actual force is the important factor. A distance less than the width of the periodontal membrane, i.e. 0.2 mm. is the ideal distance. He maintained that the shorter distance allowed the tissue to recover between adjustments. However, he did concede that if a force lighter than the capillary blood pressure was applied it would be possible to apply it over a greater distance than the width of the periodontal membrane without resorption occurring.

In January, 1938 Stuteville [136] summarised investigations carried out by him on human teeth subjected to orthodontic force and inter-alia reported that "there was a tendency for the alveolar process to remain at a certain width" and that there was more injury produced by the interfering forces of occlusion than by the forces of appliances.

In February, 1938 Stuteville [137] reported again on his experiments on dogs and humans and concluded inter-alia that all orthodontic force caused some damage to the tissues but that fixed appliances caused less than removable appliances. Also, he maintained that almost all damage was repaired after cessation of the force. In the ten cases where he quoted the force applied, the two lightest forces were on humans, one of only 5 gms,, and one of 16 gms. In the cases of the light forces used on human subjects, a lingual arch exerted a pressure towards the buccal on first bicuspid teeth. The first report was of a pressure of 5 gms, declining to 2 gms. over 51 days on a maxillary first bicuspid on a 14 year old child (sex unstated). In the second case a pressure of 16 gms. declining to 4 gms. in 51 days was applied to a mandibular first bicuspid of a 14 year old child (sex unstated). In both cases Stuteville reported resorption on the periodontal surface of the buccal alveolar bone and deposition of new bone on the buccal surface.

Recent Research.

Storey and Smith [133] in 1952 pointed out that there was no reliable data as to the magnitude of the force to be applied to give the optimal rate of tooth movement without causing damage to the tissues or pain.

Early researchers, notably Oppenheim 1930 [93], Schwarz 1932 [111], and Johnson 1932 [58] found that what they called "light" forces moved teeth effectively but with a minimum of disturbance, to the surrounding tissues.

Oppenheim referred to "mild" force as that which allowed osteoblastic activity to proceed simultaneously with osteoclastic activity and which finally allowed the osteoblastic activity to restore normal conditions. On the other hand he stated that "strong" forces are those which tear fibres and cause thromboses.

Schwarz gave as his idea of light force that which allowed continuous lively resorption to take place but did not cause necrosis.

Johnson, referring to his twin-wire appliance, stated that "the teeth are moved rapidly without discomfort to the patient and the tissues are not injured", and "while the pressure is constant, it is very light and produces physiologic tooth movement."

However, there was no agreement on what constituted a light force. Johnson's force varied from 56 gms. to 280 gms., applied to humans; Schwarz experimented on dogs and monkeys and advocated 15 gms. - 20 gms. per sq. cm. of root surface area; and Oppenheim advocated "mild" force after his experiments on dogs.

Optimal Forces.

Storey and Smith 1952 [133] conducted a series of investigations on the movement of human cuspid teeth and these experiments were the first to delineate the optimal orthodontic forces required for favourable bone reaction 1952 [124, 133]. These investigations have remained the classic in this field of research.

Fixed orthodontic appliances were used on each of five patients, aged 12 - 15 years, requiring retraction of cuspid teeth after prior extraction of the first bicuspids. Deeming 450 gms. to be a heavy force, a load of 400 gms. - 600 gms. was applied by a "clock" type helical torsion spring to one side and a load of 175 gms.- 300 gms. by a similar helical torsion spring to the other side in the case of each patient tested in the study. Each spring operated per medium of sectional edgewise arches.

The light spring caused rapid movement of the cuspid until the force in the spring had dropped to 135 gms. - 180 gms.; movement then virtually ceased. With the heavy spring the anchor unit moved initially until the force in the spring had decreased to 200 gms. - 300 gms. Then the cuspid moved until the load had dropped to 60 gms. - 115 gms. There was a force which the teeth were able to resist without appreciable initial movement, i.e. 150 gms. for the cuspids and 300 gms. for the molar/2nd premolar anchor units.

The estimated ratio of root area of cuspid to anchor unit was 3:8 and as this is approximately the same ratio of the forces causing maximum rate of tooth movement for the cuspid and the anchor teeth, it suggests that the optimal bone reaction is related to force per unit area. This optimal bone response allowed a relatively fast tipping movement of 0.1 mm. per day, centred about the apical third of the tooth. The maximum pressure and bone response occurred at the alveolar margin and zero pressure at the level of the centre of rotation.

Storey and Smith concluded that the lack of movement of the cuspid initially with heavy forces was due to undermining resorption of bone taking place, on the pressure side, as propounded by Sandstedt.

Storey and Smith 1952 [134] stated that the fact that the remaining force which the tooth could support after heavy loads had been applied was less than that which it could support after light loads had been applied, may be due to damage of the periodontal membrane by heavy forces.

Sicher 1962 [120] also referred to the damage which heavy forces may cause to the periodontal membrane. He stated that the alveolo-dental ligament has an intermediate plexus, the fibres of which slide apart to accommodate to tension. If the force applied was greater than the tensile strength of the alveolo-dental ligament, primary damage would occur on the tension side. This supports the contention of Storey and Smith concerning the decreased ability of the cuspid tooth to resist residual force after the application of heavy forces.

Radiographic Examination of Tissue Change During Tooth Movement.

Storey in 1953 [126] next conducted a series of experiments in tooth movement using radiographs, to investigate the changes taking place in the tissues surrounding the tooth both on the pressure and on the tension side. The experiments involved the movement of cuspids in the upper jaws of humans.

Using heavy forces of 200 gms. - 500 gms., he confirmed the hypothesis of Sandstedt that movement of teeth by heavy forces would occur intermittently due to undermining resorption. The series of radiographs taken in this case (sex unstated) showed no appreciable movement at 49 days. Some resorption of the lamina dura had taken place in the tension regions and radiolucent areas were showing at the pressure regions. A second radiograph 21 days later showed considerable movement into the resorbed pressure areas. There was very little formation of bone in the tension areas; at 84 days the final radiograph showed a similar picture.

In the case of a female patient where optimal force of 200 gms. - 160 gms. was applied, an average rate of movement of 0.75 mm. per week was sustained for 6 weeks. Storey reported bone giving a radiographic appearance of lamination being laid down on the tension side with trabeculae apparently orientated in the line of stress.

Another case of a male patient showed the result of a low initial force of 100 gms., being subsequently increased to 200 gms. at 74 days. A radiograph taken at this time showed a layer of radiographically dense and apparently laminated bone at the tension area and a radiolucent area marking the position of the original lamina dura. Formation of dense bone also showed on the pressure side. There was movement of 1.74 mm. in these 74 days.

When the pressure was increased to 200 gms., further movement of 1.25 mm. took place in 24 days. A radiograph taken then showed continued formation of dense bone at the tension side with following resorption, and dense bone on the pressure side.

Finally the movement of upper cuspids in a female patient was radiographed. An initial force of 100 gms. was applied to the upper left cuspid and after 9 days the tooth moved from the lamina dura. At 15 days formation of bone was seen in these tension areas, and by 24 days the movement was marked (1 mm. in 9 days). Between 24 and 51 days the movement decreased. A new lamina dura formed and showed on radiographs on the 45th and 51st days. Then on the 72nd day a radiograph showed that further significant movement had occurred as a new lamina dura had formed and resorption of the old one was in progress. In the pressure areas, periodontal space and lamina dura could be seen which meant that continual formation of lamina dura had preceded the pressure resorption in front of the moving tooth.

The upper right cuspid was also moved but the spring was activated one week later than that on the upper left cuspid. However, by radiographs, the movement was seen to have occurred at the same time on each tooth and was related to the actual period, not the timing of the activation of the springs.

Storey observed from these experiments that when using forces within his optimal range the formation of bone on the tension side was deposited with the trabeculae orientated in the presumed line of tensile stress. He concluded that the periodontal membrane and bone on the tension side were still supporting some of the force applied to the tooth, and moderating the degree of pressure on the pressure side.

He noted the resorption of the newly formed dense bone on the tension side and its replacement by spongy bone. Also, he noted that on the pressure side there was an area where the lamina dura was being formed ahead of the resorption.

With heavy forces there was no movement until the undermining resorption was completed and resorption of bone occurred at the alveolar crest on the tension side.

The appearance of bone laid down on the tension side was different with the different forces. Light force caused dense bone and trabeculae apparently orientated in the lines of force. With heavy forces the bone was less dense and the trabeculae were not orientated in the presumed line of stress.

With the light forces of under 100 gms. he noted a cyclic behaviour in the bone response in the case of the female compared to continuous response in the case of the male. A difference in the type of newly formed bone was also noted. In the male the movement was almost continuous and long trabeculae formed in the tension side. Intermittent movement was seen in the case of the female and dense bone was laid down only when movement was almost stopped.

Influence of the Menstrual Cycle on Orthodontic Movement.

In 1954 Storey [127] conducted a series of experiments which related tooth movement in the female to the menstrual cycle.

He used cuspid retraction springs which applied a constant continuous force of 175-300 gms. as described in his previous experiments on human subjects (1952 [124]).

In several cases the results showed a cyclic variation which indicated that the fluctuation in the rate of tooth movement was related to some factor other than the time at which force was first applied. This was demonstrated by applying force to cuspids in the same jaw, 14 days apart, and observing that they experienced the same variations in movement rate.

The results from the male cases, whilst showing variations in the rate of tooth movement, showed no cyclic variation.

Another series of female patients were studied and medical histories of sexual function were obtained. It was found that the cycle of tooth movement and the menstrual cycle were related. The maximum rate of tooth movement was observed in the second half of the menstrual cycle and was usually followed by a significant decrease during the fourth week.

Storey found that the cyclic variation was present in some patients even though menstruation had not begun. He pointed out that excretion of oestrogens becomes cyclic about 1½ years before the commencement of menstruation. He also noted that where menstruation was irregular, there was no regular variation in bone change.

The variations in weekly rate of movement between the cuspids and anchor teeth in the male patients fluctuated irregularly between approximately 0.5 mm. to 1 mm. With the female patients the variations in rate were cyclic and fluctuated between approximately 0.25 mm. and 1.25 mm. of movement per week.

Storey stated that, as the variations in the rate of tooth movement were not related to the time at which the force was first applied, it was unlikely that they resulted from a repeated process of undermining resorption.

He suggested that the variations in bone changes appear to be under control of the hormones responsible for the changes occurring during the menstrual cycle. Storey drew attention to the constant relation of citric acid secretion to the menstrual cycle, the maximum amount being secreted during the second half of the menstrual cycle. Also the serum calcium level rises at this time and is associated with increased bone resorption. He hypothesised that there was a significant link between the increased citric acid and serum calcium level on one hand, and increased tooth movement on the other, the latter presumably resulting from increased bone resorption.

Storey concluded that both cycles are related to the same cause, namely the increased resorption and decreased formation of bone which occurs at this time during the menstrual cycle. He stated that as the oestrogenic hormones are known to interfere with the growth of bone, it is probable that they are responsible for the bone changes observed during the menstrual cycle. As these hormones are under the control of the anterior lobe of the pituitary gland,the cycle of variation in the rate of resorption and deposition of bone, and thus the movement of teeth, is due primarily to the rhythmical variations in the activity of the anterior lobe of the pituitary gland.

Degree of Force and its Duration Related to Tooth Movement.

Following up his limited investigations on human patients, Storey in 1955 [128], [130], [131], performed experiments related to tooth movement on rabbits, rats and guinea pigs. These experiments related to the degree of force, its duration and the effect of age and sex on tooth movement. Histological examinations were made at various stages.

He found that the lateral movement of the premaxillary bones in the rat and the rabbit contributed to tooth movement and thus tended to give a false indication of the rate of tooth movement through bone. This was not the case with the guinea pig. When moderate forces were used on the guinea pig, the initial movement was found to be movement of the tooth in the socket and not movement through bone. There was then a pause for 2 - 3 days while vascular and cellular changes occurred. The periodontal membrane was disrupted on the tension side and was compressed against the alveolar crest on the pressure side. Osteoblasts had formed on the tension side and calcification started at the bone - periodontal membrane junction. Resorption of the alveolar process started on both the pressure and tension sides. Trabeculae apparently orientated to resist the applied force, formed on the pressure side ahead of the area of resorption. This bone was very cellular. This process continued, and on the 9th day the trabeculae were thicker and the newly formed bone on the pressure side was undergoing resorption. By the 14th day it was difficult to distinguish between the new and old bone by its texture.

The use of heavy forces led to decreased cellular activity on the pressure side and increased destruction of the periodontal membrane on the tension side. This was followed by increased cellular activity and formation of immature and poorly calcified trabeculae. However, with light forces the trabeculae were more mature and thicker.

Storey also pointed out the great increase in vascular tissue associated with rapid bone resorption. He hypothesised that the resorption of bone was begun by a vascular process which dissolved the bone salts and left the bone matrix projecting. This was then resorbed by the osteoclasts. Vaughan 1970 [151] quotes work by Reynolds in 1968 which supports this observation by Storey. In the histological preparations Storey saw a red stained line between the osteoclast and the bone when the bone was actually undergoing resorption. It appeared to be continuous with the bone and was thought to be bone matrix and indicating that the osteoclast was associated with removal of the matrix but not necessarily the bone salt.

He suggested that these observations led to the conclusion that the initial bone resorption stage was that of bone salt removal which was self-limiting by the increasing layer of bone matrix which was exposed. The osteoclast then removed the matrix and both processes proceeded in turn.

From his observations during these experiments on animals Storey concluded that there was a limit to the length of time that a force may be applied to a tooth. This limit was the amount of bone available to the tooth to move in. He found that a light force could move a tooth through a thin lateral plate of bone as the resorption took place faster than the rate of deposition of bone. He advocated periods of rest in these cases, to allow formation of bone ahead of the movement.

Effects of Age on Tooth Movement.

The experiments with respect to the effect of age on tooth movement showed that the rate of movement of the older animal eventually equalled that of the younger animal, though there was an initial lag in the rate. There was a significant increase in the time taken for comparable tooth movements. With older animals the bone laid down on the tension side was more mature and the trabeculae are shorter and thicker and there was a more regular arrangement of osteocytes. There was a greater distance between the blood vessels in the new bone and between the osteocytes. Bone resorption was also slower in the older animal. The existing blood vessels and bone cells were spaced further apart and there was an increased amount of bone salts per unit volume to be removed by this reduced cellular and vascular formation.

Difference in Bone Response Related to Sex.

There was a slight difference in the response of the bone related to the sex. The main dissimilarity was in the degree of maturation, the female animal having the more mature newly formed bone. Storey thought this may be due to a difference in biological age.

To summarise the work of Storey in conjunction with Smith in 1952 [124, 133], and then Storey's own investigations from 1953 to 1955 [126, 127, 128, 130, 131]:-

(i) The principle of an "optimal orthodontic force" was confirmed and given a value for human mandibular cuspid teeth.

(ii) Light, optimal, and heavy orthodontic forces were given meaningful values.

(iii) The fact of undermining resorption of bone with heavy orthodontic forces was confirmed.

(iv) The effects of bone response were found to be related to the duration of orthodontic force, and the age and the sex of subjects examined.

Storey and Smith 1952 [124, 133], pointed out that there would be a variation in orthodontic force required as between patients because of differences in age, sex, health and in the surface areas of the teeth. They disagreed with suggestions by Oppenheim 1944[95] and Gottlieb 1956[42], that the differences between patients were too great to allow any standardisation of the range of forces.

Referring to these experiments of Storey and Smith, Begg and Kesling 1971[17] have written ".. their contributions are of outstanding value to orthodontics."

Bone Changes with very Low Orthodontic Forces.

Botting and Storey 1973[21] performed experiments on 21 guinea pigs to determine the bone changes induced by very low orthodontic forces. They stated that the range of force necessary to move teeth without excessive tissue damage will differ in each species due to differences in size of teeth, nature of soft and bony tissue and difference in metabolic rates. Their assumption was that for maxillary incisor teeth of guinea pigs 3 - 7 gms. was a light force and 30 - 40 gms. was a heavy force.

Helical torsion springs were applied intra-orally to avoid interference by the animal and were active for up to 21 days.

Serial histological sections were cut in a horizontal plane and at 30° to the coronal plane. Botting and Storey claimed more accuracy in interpretation by this method.

With heavy forces, the periodontal tissues on the pressure side were compressed by the first day.

Subsequently, tooth - bone contact occurred and undermining resorption was initiated. Frontal resorption was observed for a considerable distance above and below the area of contact. The lateral alveolar crest was removed by resorption and the contact area then moved further up the alveolar plate.

New bone trabeculae were noted growing on the periosteal aspect of the lateral alveolar plate and orientated in the direction of the applied compressive force.

On the tension side, the periodontal fibres were disrupted near the alveolar crest after three days. Continuing new bone formation occurred with an increase in mitotic activity of the connective tissue cells in the adjacent tissue. New trabeculae were arranged in lattice form, orientated in the apparent direction of tension.

With light forces, there was no bone resorption noted on the pressure side for several days. By the sixth day tooth - bone contact occurred with resulting undermining resorption. Trabeculae were seen growing from the periosteal aspect of the lateral alveolar plate, but not as extensively as was the case with the heavy forces.

On the tension side there was no sign of disruption of the periodontal fibres. There were definite signs of new bone formation at the alveolar crest of the tension side after five days. By the 14th day there was less bone formed than was seen with the heavy force.

The maxillary incisor teeth which were normally in contact were separated after the heavy force had acted for 21 days, approximately 10 mm. at the incisal edges. The light force caused a separation of about half this amount.

Botting and Storey noted that even with the use of very light orthodontic forces to the teeth of guinea pigs, the process of bone resorption is still one of undermining resorption adjoining areas of compressed periodontal tissue. Also, definite tooth - bone contact occurs with very light forces. With the heavier forces, the bone resorption occurs over a much greater area and growth occurs more rapidly and to a greater extent up the lateral periosteal bone margins than with the light forces.

Botting and Storey suggest that two processes occur. Firstly, as a result of the compressed tissue and resulting necrosis, an inflammatory reaction causes undermining bone resorption. Secondly, compressive stress induces strain in the lateral alveolar bone which is relieved where there are discontinuities in the bone such as vascular spaces and osteocyte lacunae. They state that this induces rarefaction along preferred planes and suggest that piezoelectric phenomena may be involved. They also observed that frontal resorption, adjacent to the undermining resorption played a large part in the process of bone removal with heavy forces.

Botting and Storey concluded from these experiments that the rate of tooth movement and tissue reorganization depend on the compressive and tensile forces applied per unit area of tissue by teeth. When these forces are excessive, tissue disruption takes place and, when very light, very slow remodelling of soft and hard tissues is caused. In each species there is an optimal range of force to induce a clinically acceptable rate of tooth movement and reorganization of tissues without undue disruption.

THE EFFECT OF ORTHODONTIC BIOMECHANICS ON BONE RESPONSE.

The application of force to a tooth and its mechanical response are the basic influences which cause the remodelling of bone and orthodontic tooth movement.

These two areas of orthodontic biomechanics, tooth movement and appliance design, have been reported on by Burstone 1962[25], 1969[26], and the following is taken from these studies.

Tooth Movement.

The centre of resistance to movement through bone in a single rooted tooth with parabolic shape is at a point 0.4 times the distance from the alveolar crest to the apex. The centre of resistance is coincidental with the centroid which in this case is the geometric centre of that part of the tooth between the crest and the apex. A force acting through the centroid would produce pure translation. However, it is not possible to apply such a simple force in the mouth. A pure moment applied to the tooth would cause rotation about the centroid.

To obtain bodily tooth movement, a suitable ratio of a horizontal force and moment must be applied to the crown of a tooth to cause the equivalent of a force acting through the centroid. When this occurs, the centre of rotation is said to be at infinity.

As tooth movement takes place the ratio of the moment to the force may be modified by dissipation of one of the components at a faster rate than the other.

The magnitude and direction of the applied force are the only variables associated with tooth movement which are under control of the orthodontist.

Force magnitude directly affects the rate of tooth movement. At lower force magnitudes, increases in force cause increased rates of tooth movement by direct bone resorption on the pressure side of the tooth. At higher force magnitudes, increases in force cause hyalinization of the periodontal membrane on the pressure side which in turn causes a lag in movement. After undermining resorption has occurred, a spurt in movement takes place and the tooth moves very rapidly into the new space.

A wide range of forces from light to heavy, provided that they are continuous, are capable of rapidly moving teeth.

The generation of pain is one of the limiting variables when force on a tooth is increased. The pain can be immediate, such as response from a sudden heavy force, or delayed, which can arise from a variety of force magnitudes.

The optimal force is that which produces a rapid rate of tooth movement, without discomfort to the patient, and initiates a maximum cellular response.

Appliances.

Orthodontic appliances are the tools which control the centre of rotation of teeth during tooth movement, produce optimal stress levels in the periodontal membrane and bone and maintain nearly constant stress levels as movement takes place.

All appliances have active members concerned with tooth movement and reactive members which function for purposes of anchorage.

There are three important aspects of these members to be incorporated in appliance design.

The moment-to-force ratio must be considered in both active and reactive members. An example of the latter case is where anchorage is being considered after extractions, when it is necessary to introduce a moment moving molar roots in the bone mesially, and crowns posteriorly, by use of anchorage bends in archwires. The moment-to-force ratio controls the centre of rotation of a tooth or group of teeth.

The load - deflection rate is involved with the delivery of a relatively constant force. As the load - deflection rate becomes lower the change in force value is lessened as a tooth moves through bone under a continuous force.

An appliance with a low load - deflection rate in its active members will maintain an optimal stress on bone for a relatively lengthy period. Also, there is greater accuracy in control over force magnitude with low load - deflection rate members.

In the reactive members, the load - deflection rate should be high, tending towards rigidity. The anchorage effect of a group of teeth is enhanced if the teeth move in bone as a unit.

Maximal elastic load is the greatest force, or moment, that can be applied to a member without producing permanent deformation. There should be a margin of safety incorporated in tooth active and reactive members to enable the appliance to withstand an accidental overload.

The mechanical property which determines the load - deflection rate is the Modulus of Elasticity. This value is fixed for each metal alloy and cannot be altered, except by using another alloy.

Wire cross-section greatly influences both the load - deflection rate and the maximal elastic load. The load - deflection rate varies as the fourth power of the cross-section of round wire and the maximal elastic load as the third power of the cross-section of round wire.

With active members, decreasing the cross-section with the purpose of reducing the load - deflection rate can lead to permanent deformation by the concurrent rapid decrease in maximal elastic load and loss of optimal stress on bone.

With the reactive members, to prevent movement of teeth in bone, the wire cross-section should be large enough to have a sufficiently high load - deflection rate to confer rigidity on this section of the appliance.

The load - deflection rate varies inversely as the third power of a cantilever arm. The maximal elastic load varies inversely as the length of a cantilever arm.

Lengthening a cantilever arm markedly reduces the load-deflection rate but the maximal elastic load is not greatly altered as it varies linearly with the length.

Extra length of wire can be incorporated in loops or helices.

Adding extra coils at the point of support of a cantilever lowers the load - deflection rate by adding length of wire. This does not alter the maximal elastic load if the point of application of the force and point of support remain the same distance apart.

Stress raisers, such as nicks in the wire and sharp bends, should be avoided as they lead to premature deformation.

Sections of <u>maximal stress</u> should have wires of adequate thickness. Areas of soldering cause lowering of the elastic limit in a wire if there is overheating.

Soldering can cause sudden changes in cross-section, from where a double wire becomes single, for instance. These areas are also areas of maximal stress.

The direction of loading of a bent wire should be in the same direction as the original bend. This is because the wire is more resistant to permanent deformation as some residual stresses remain in the wire after the placement of the first bend. For this reason an anchorage bend in an arch wire should be overbent and slightly straightened. The loading will then be in the same direction as the last bend.

The attachment of the wire to the tooth should allow the correct force and/or moment to be applied to the tooth by being long enough with deep enough slots for proper and secure fastening. However, the attachment should allow the wire freedom to slide if necessary. It should not be so long that there is insufficient wire between teeth or the point of support to allow adequate flexibility and thus maximum load - deflection rates to be achieved.

The main object to be achieved with active members of an appliance is the delivery of a long acting continuous constant force through the tooth to bone to gain the optimal orthodontic result.