The Effect of Force on Bone and Bones

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Macroscopic Changes

While bone changes associated with tooth movement have been studied intensively,[1,2,3,4,5] alterations induced in craniofacial structures by the direct application of force have received less attention. There are several reasons for this: first, it is difficult to apply controlled force to bone; secondly, it is not easy to estimate the pressures and tensions applied to and within bone, and thirdly, it is difficult to analyze the effects of stress on living bone and bones. However, the further development of orthodontics requires better understanding of the effects of applied forces on the craniofacial complex and better definition of the limitations imposed on orthodontic treatment by growth processes.

The development of the dentofacial area is complex, involving three different skeletal growth systems, namely, endochondral, sutural and appositional growth of bone. To investigate the effects of stress on such complex growth systems poses many problems in the present state of knowledge. It would simplify the problem if a comparison could be made first of the effect of similar stresses on individual growth systems. Little information is available on this subject for, while workers have applied different forces to different skeletal structures in different ways, the forces used have not been defined sufficiently to allow reproduction of experiments by other investigators; different animals have been examined, so strict comparison of effects is not possible; sequential changes have not been studied and consequently the histological pictures described are inadequate. In previous work on bone changes associated with tooth movement some of the objections described above were overcome but, as force was applied to teeth to induce lateral movement of the premaxillae, the stress imposed on bone was not known.[4] However, the experimental technique used affords considerable scope for studying the effects of abnormal stress applied directly to different parts of the skeleton. This present paper describes (1) the adaption and use of helical torsion springs to exert force directly to bone and bones; (2) associated macroscopic changes on skeletal tissue and (3) sutural and endochondral growth systems.

Experimental Methods

Pilot experiments demonstrated that helical torsion springs could be attached easily to bone and bones without unduly worrying animals or inducing infection in underlying tissues. The basic spring is fabricated from 0.016 round 18.8 austenitic stainless steel wire with an ultimate tensile strength of 376,000 lbs. to the square inch. It consisted of two arms and a number of loops of wire formed on a spring winder of 0.020 diameter mandrel.[4]

The size and shape of the spring was determined by two factors, the force required and the location of the spring in the animal. For example, when springs are attached to the parietal bones, they must fit neatly between the eyes and ears of the animal and close to the skull to avoid being dislodged as the animal rubs its head against the cage, feeding container or its litter mates (Figure 1). The dimensions of the spring need to be modified in

Fig. 1 Photograph showing guinea pig with a helical torsion spring attached to the skull and applying lateral force to the interparietal suture.

order to apply similar forces to different bones. For example, to lower the force applied to bone and yet maintain the same arm length, the number of coils of wire in the loop can be increased by winding a second lamination over the first layer of wire coils. As many as forty turns may be placed in the spring in this way while retaining the size of the spring loop within reasonable working limits. The increased number of turns in the wire loops alters the load-deflection characteristics of the spring so that a lighter force is applied over the same range of deflection. In the present experiments spring loops were formed with five coils of wire arranged in two laminations with arms approximately 10 mm long. So that calculations of pressures at the bone spring interface were easier to make, 0.016 square cross-section wire was used in some experiments. The number of coils was increased to seven to maintain a range of force similar to that exerted by round wire springs.

Other modifications are required to retain springs in the living animal. In order to prevent the arm of the spring slipping into the bone, helical torsion springs were constructed with loops of wire placed at the ends of the arms where they penetrate the bone. These were adjusted to stand the springs far enough away from the skin or the fur to prevent interference with spring action or irritation to tissues (Figure 2).

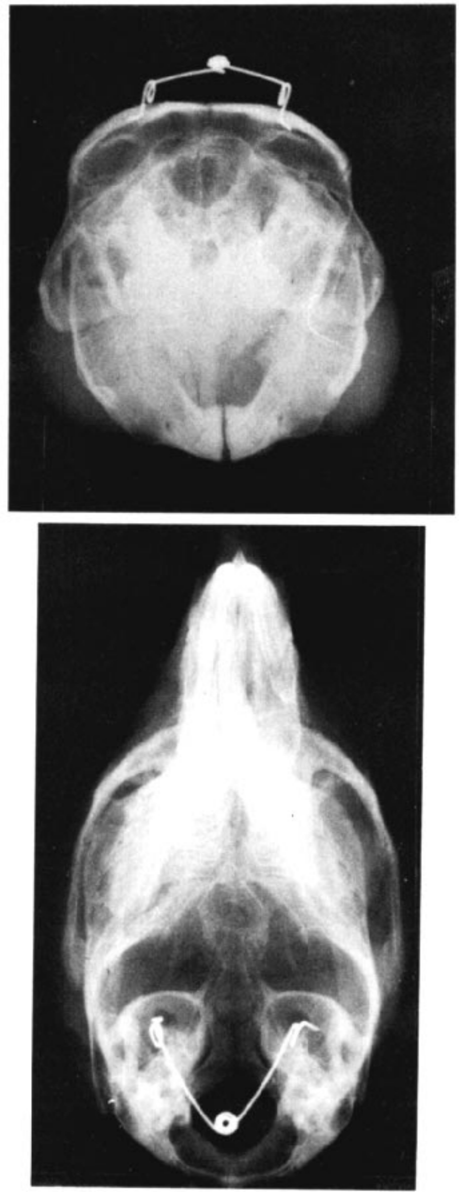

Fig. 2 Radiographs of guinea pig skulls with helical torsion spring attached to the parietal bones showing loops holding the arms away from the bones and the ends of the wire bent to make springs self-retaining. Above, Posteroanterior view. Below, Dorsoventral view.

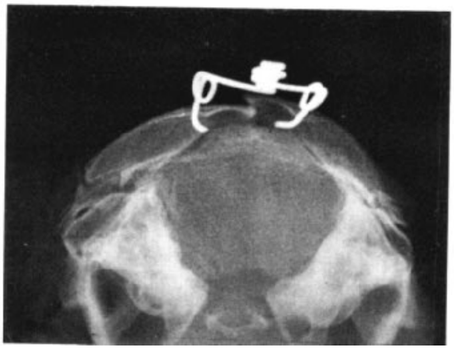

Fig. 3 Radiograph of the guinea pig skull in the anteroposterior plane showing helical torsion spring adjusted to apply pressure at the sagittal suture after twenty days. The parietal bones have moved together and past one another. Note that the arms are bent medially to aid retention of the spring.

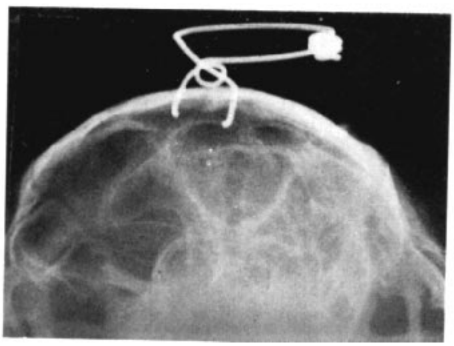

Fig. 4 Radiograph of guinea pig skull in the anteroposterior plane showing helical torsion spring with an additional loop in one arm to control the direction of applied force. The two parietal bones have abutted together after force application for thirty-three days.

The helical torsion spring can be adjusted to exert pressure as well as tension on bone. In preliminary experiments it was found that, although pressure could be applied at the sagittal suture, the arms of the spring tended to twist so that the direction of applied force altered. This resulted in the cranial bones moving across one another. In some cases springs twisted to such an extent that they applied tension instead of compression to the tissues

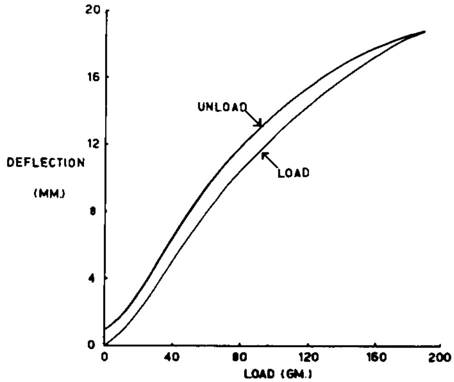

Fig. 5 The load-deflection curve of a helical torsion spring during loading and unloading showing slight permanent deformation. In experiments the force used was in the range 80-150 gm.

(Figure 3). In order to prevent springs twisting an additional loop was placed in one arm so that the other arm could slide through it (Figure 4).

The Measurement of Forces Applied by Springs

The load-deflection characteristics of each spring were measured on a cathetometer. A typical curve is shown in Figure 5. Springs were designed so that the load applied in vivo was less than the elastic limit of the wire in order to prevent significant permanent deformation during experiments. This was confirmed by retesting springs after use in vivo and demonstrating that their load-deflection curves were not significantly changed. Consequently the deflection of the wire arms can be measured and the force applied during bone changes in vivo calculated with reasonable accuracy from the predetermined load-deflection curves of particular springs. In the present experiments an initial force of the order of 150 gms was applied both in pressure and tension to different growth systems.

Operative Techniques

General: Guinea pigs (200 gms) were

anesthetized with open ether. The skin was shaved at the site of operation and swabbed with 2% iodine. Each animal was injected interperitoneally with tetracycline hydrochloride (25 mg per kg body weight per day) for three days to prevent infection in the operative areas, and to act as a marker to study bone growth. Spring holes in bone were made by drilling slowly at 5,000 revolutions per minute with a round dental drill (size ½), care being taken to avoid heating bone. Alternatively the ends of spring arms were sharpened and pushed through the bone. After operation, skin margins were sutured together and the area sprayed with Norbecutane. At the conclusion of experiments animals were killed with ether anesthetic and specimens removed for histological study and fixed in 10% formol saline. All animals were kept in smooth-walled plastic cages, fed Barastoc pellets, greens and given water ad lib.

Insertion of springs and markers: In the cranial vault a single incision was made in the skin across, and at right angles to, sutures. Holes were drilled through the bone approximately 7 mm apart and equidistant from the suture being studied. The ends of the spring arms were curved in the direction of force application in order to increase the retention of the appliance (Figures 2, 3 and 4). One spring arm was inserted into a hole in the bone and the other held firmly in pliers, the spring contracted and the other spring arm twisted into the opposite hole. Once inserted, the shape of the spring arms made the appliance self retaining.

In the tibia an incision was made in the skin adjoining the lateral aspect of the thigh and extended down below the knee. The skin was reflected laterally to expose the epiphysis and metaphysis. The ends of the spring arm were sharpened to a fine needle point. One arm of the spring was pushed through

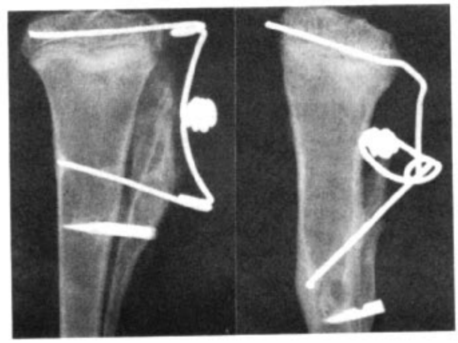

Fig. 6 Radiographs of the upper end of the tibia of guinea pigs showing helical torsion springs attached to the epiphysis and metaphysis to apply stress at the endochondral growth site. Left, spring adjusted to exert pressure. Right, spring constructed with retaining loop in arm to exert pressure.

the epiphysis and the other through the diaphysis (Figure 6). In growing long bones great care was taken that the spring arms passed through the epiphysis and avoided the epiphyseal and articular cartilages. Sharpened ends of the wire were then bent at right angles to retain the spring in the bone and the excess cut off to prevent tissue irritation. In the same animal, springs and markers were inserted in one leg and markers only in the other, the control leg.

Stainless steel pins were inserted in bone to act as points of reference to measure growth changes.[6] Pin ends were sharpened and forced into bone under firm pressure; the excess metal was then cut off and the stainless steel point pushed firmly into the bone. In the cranium, pins were placed just lateral to the spring ends so that a change in the distance between the two pins in the radiograph measured the amount of bone movement, while measurements between spring ends showed the amount of spring movement through bone. In the tibia, markers were placed in the diaphysis, usually 3-4 mm from the spring arm.

Measurement of Bone Changes

A standardized method was developed so that comparable radiographs could be superimposed and bone changes determined accurately. Anesthetized animals were placed face down on a plastic animal holder. The head was held rigidly by two rods inserted into the external auditory canals with the skull resting on a plastic shelf. The hind legs were fastened with cord in an extended position with the knee joints abducted. Radiographs were taken on Ilford No. 5 film with the tube film distance 60 cm, with an exposure of 0.8 seconds at 45 Kv. The films were developed by a standardized procedure.

Radiographs were projected at a magnification of five and the general outlines of the bones, positions of springs and markers drawn on the paper. In the skull the distance between the spring arms and markers was measured but it was not possible to determine the suture line with any accuracy. In the tibia a line was drawn at right angles to the bone shaft across the lowest point of the epiphyseal bone. A line perpendicular to this was drawn to the point of the marker and the distance from the epiphyseal plate to the marker measured. Similarly the distances from the epiphyseal line to the spring arm were also measured.

Results

1. *The effect of tensile and compressive stress applied to bone tissue*

When a round wire spring adjusted to exert either tensile or compressive force of the order of 150 gm was inserted within a growing cranial bone, little movement of the spring occurred initially, at the most 1 mm in fourteen days, and very little thereafter. During the same period of time, movement of markers was not observed in experimental or control bones. Similarly, in growing long bones, arms of springs moved no more than 0.5-1 mm through the compact bone of the diaphysis, although in the trabeculated bone of the epiphysis, arms sometimes moved 2-3 mm. When this occurred, the angle of the spring arms relative to the bone shaft changed. Macroscopic examination of the skull and tibia showed little change except for thickening of bone and connective tissue at the site of entry of the spring arms into bone.

In order to estimate the pressure applied at the bone-wire interface, square cross-sectional 0.016 wire was inserted into the parietal bone in sites known to have little or no marrow cavity. The thickness of the bone was measured with a micrometer screw gauge and in each case was of the order of 0.050. Little movement of spring arms occurred in vivo up to forty days. The pressure at the bone-wire interface was calculated to be of the order of 250 lb. to the square inch (175 gm per square mm).

2. *The effect of mechanical stress applied to bones connected by sutures*

(a) *Tensile force applied to cranial bones.* In control animals, lateral movement of parietal bones occurred at a steady rate, bone separating 1-1.5 mm in forty days. Tension applied across the midsagittal suture at the level of the parietal bones induced a rapid lateral movement of the bones for the first fourteen days. Then the rate of movement slowly decreased until it approximated that seen in the control animal (Fig. 7); the markers moved apart approximately 4-5 mm in forty days while the total movement of both spring arms was a maximum of 2 mm more than that of the markers. Unlike the markers, the spring arms first moved rapidly then remained stationary until the end of the experiment. In one case, when the spring was removed at fourteen days, although the rate of bone move-

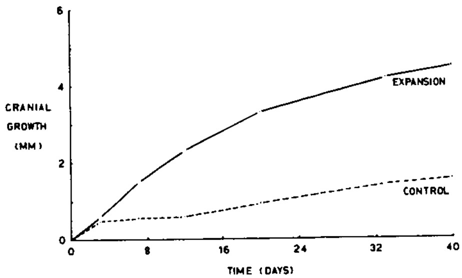

Fig. 7 Graph showing the rate of lateral movement of the parietal bones during normal growth and under increased lateral force. Rapid expansion of the cranium occurs initially with increased lateral force.

ment slowed, it still continued at approximately the same rate as that in control or other experimental animals (Figure 8).

In addition to alteration in the rate of bone movement, cranial morphology was significantly changed. In the coronal section the parietal plates of bone were thickened, particularly in the lateral aspect around spring arms. The normal structure of the suture was changed from a thin dark band to a translucent sheet of connective tissue, still connecting the two bones. The well-defined bony margin of the suture was no longer detectable. In addition, changes had taken place in adjacent bones. Direct measurement of sutural

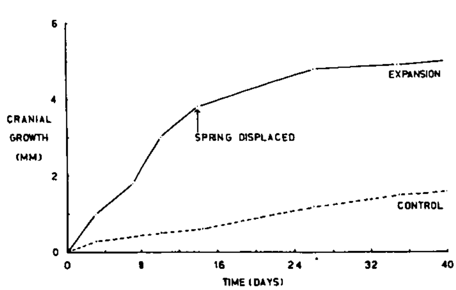

Fig. 8 Graph showing rate of movement of parietal bones in the normal animal and one where high tensile forces were exerted for fourteen days. After spring was displaced growth slowed but followed a similar path to that seen in the control animal.

width was made by transilluminating the cranial bone from within the skull after removing the brain. In normal animals the sutures were approximately 0.5 mm wide. In animals with parietal bones moved laterally under increased tensile stress, the sutures were up to 3 mm wide while the interfrontal suture at its parietal aspect was 1.5 mm wide, tapering to 0.5 mm at the nasal end of the bone. The frontoparietal sutures were also wider with bone margins curved in the direction of movement (Figure 9).

(b) *Compressive stress applied to cranial bone.* In experiments using a compression spring with little lateral stability the cranial bones slid past one another for some considerable distance. This was shown radiographically (Figure 3). Subsequently, with modifications in the form of the spring, macroscopic examination of the skull after twenty-one days compression showed that the suture line was obliterated and the two parietal bones were abutted (Figure 4). By forty days little further change occurred. Sections of parietal bones were removed from the skull at post mortem and manipulated manually. Unlike the control bones which exhibited considerable movement at the suture line, compressed bones did not and, when stressed, the adjoining bone fractured instead of moving at the suture. Undecalcified histological sections confirmed that these sutures were united by bony tissue.

Movement of bones occurred initially at a similar rate to those in the control animals but then decreased. The difference in movement was only of the order of 1 mm, and during the period of observation could not be regarded as significant. Measurements of the spring arms were considered unreliable because of a tendency of the compression spring (unlike the tension spring) to move about in the holes drilled in the cranial bone.

Fig. 9 Photograph of transilluminated guinea pig cranium with helical torsion spring applying tension to parietal bones after forty days. The interparietal suture is widened and new bone trabeculae orientated in the direction of bone movement are shown as two irregular dark bands between ill-defined bony margins and light translucent sutural connective tissue. The interfrontal suture is slightly widened.

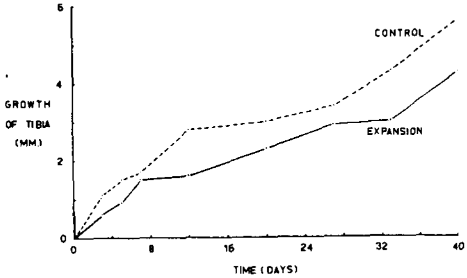

Fig. 10 Graph showing the rate of growth of control bone is greater than one where the endochondral growth site is under high tensile stress.

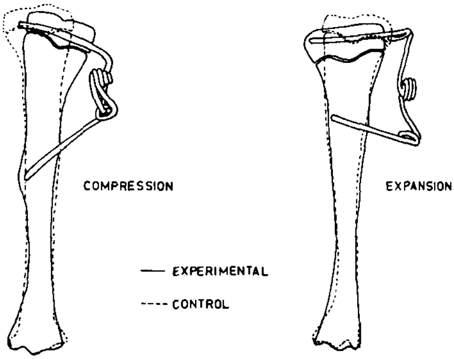

Fig. 11 Drawing of the changes in the tibia following the insertion of compression and expansion helical torsion springs. This shows that in both cases growth was decreased and perverted.

3. *The effect of mechanical force on growing endochondral cartilage*

(a) *Tensile force applied across the epiphyseal cartilage.* When tensile stress was exerted across the epiphyseal plate of the tibia, longitudinal growth was inhibited slightly (Figure 10) and the growth pattern changed. Radiographs taken· in a dorsoventral direction showed that the epiphysis of the experimental leg was no longer at right angles to the long axis of the leg. The shaft of the tibia had grown more on the lateral aspect of the bone where the spring arms were attached (Figure 11). The superimposed radiographs of experimental and control tibiae showed deviation of growth, for while the shaft of the control bone is relatively straight, the experimental bone is curved.

(b) *Compressive force applied across the epiphyseal cartilage.* Following the insertion of a compressive spring there was a slight decrease in rate of growth of the experimental leg. Subsequently the control leg grew more rapidly than the experimental one, so that after forty days there was a difference of 2 mm in the lengths of the bones (Figure 12). Examination of the springs showed that the arms had closed together to the same extent that the experimental leg had grown. Superimposition of dorsoventral radiographs of the tibiae showed a deviation of growth towards the lateral aspect of the leg on the side where the spring was inserted. In contrast to the relatively straight control bone shaft,

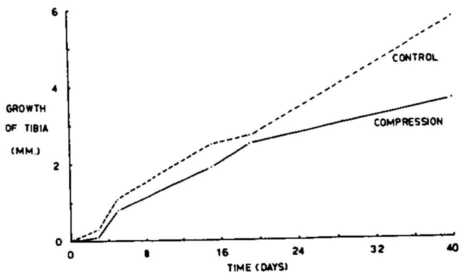

Fig. 12 Graph showing that the rate of growth of the control bone is greater than one where the endochondral growth site is under high compressive stress.

the one under pressure was curved toward the lateral aspect of the leg.

Discussion

The effect of abnormal stress on bone and bones in vivo by use of helical torsion springs permits considerable control of the degree, direction and duration of force application. The adaptation of these springs enables a wide range of continuous force to be applied by a relatively small appliance in contrast to the heavy intermittent loads exerted by most orthopaedic or orthodontic mechanisms. The stainless steel springs used had a steep deflection-load curve, so that considerable movement of the spring arms could occur before the force decreased significantly. This permitted the application of a relatively constant continuous force to bone and bones. The forces applied were well below the elastic limits of the material so little permanent deformation of wire occurred during experiments. Consequently, reasonably accurate estimates of the force applied at any particular time could be made by reference to the load-deflection curve established prior to the insertion of springs in bone.

The general nature of skeletal changes under abnormal stress is illustrated well in these experiments. Force applied directly to bone tissue produces only localized change around the area of holes drilled in bone, particularly dense lamellar bone. In cancellous bone, such as the epiphysis or metaphysis, some movement of spring took place. The movement of wire through bone probably depends on the surface area of wire in contact with bone, the type of bone and the blood supply to the area. Calculations show that the pressures at the bone-wire interface in the skull are of the order of 250 lb per square inch. This is well below the value, 8,000-10,000 lb per square inch, at which permanent deformation of bone occurs in in vitro tests.[7,8] Lack of movement of wire through the parietal bone in vivo at this force level is surprising in view of the rate at which teeth can be moved through bone by orthodontic appliances applying similar forces. This difference is associated with the presence of a peridental membrane between the tooth and bone and consequently a better blood supply permitting resorption of tissue. Although even here when high forces are used, resorption is inhibited and tooth movement impeded.[1]

In contrast to lack of movement of wire through bone, a similar force applied across sutures induces a remarkable change in the form and size of the skull. This is due to rapid change in sutural connective tissues. Under tensile force the sutural space widens, bones move laterally and the brain and meninges rapidly fill the cranial cavity. Subsequently the rate of lateral movement of bone returns to near normal as the applied force decreases. That this is not directly due to the decrease in the force exerted is shown in animals where springs were dislodged or removed after the first two weeks' expansion. Here, cranial enlargement continued at a near normal rate although the suture space was still clearly widened. The initial rapid enlargement of cranial contents probably represents tissue adaption to the altered intracranial pressures, but whether this is due to expansion of brain tissue or extracellular fluid increase has not been elucidated. Subsequent enlargement of the cranium at a normal rate after removal of excessive mechanical stress must be due to continuation of growth processes. That these can occur despite the grossly widened suture-space supports arguments that the suture is not a primary but a secondary growth site.[9]

The effect of continuous compressive forces on cranial bones depends on whether the bones abut or slide across one another at the sutures. It is difficult to maintain two flat bones in edge-to-edge contact and, with slight changes in the direction of applied force, they tend to slide past one another. When this happens, sutural connective tissue elongates while still connecting the two bones. By contrast, when bones abut, the degree of movement under pressure is insignificant; sutural fusion occurs and lateral growth of the parietal bone at sutures ceases. Although many hypotheses have been advanced to explain normal and premature sutural fusion, the process is not well understood.[10,11] It is likely that fusion of bones can only occur as a result of disassociation in the rate at which the two processes, apposition of bone at sutural margins and movement of bones, occurs. Fusion of bones will eventuate if appositional growth is excessive or where cranial expansion is restricted and bones are immobilized. The present experiments illustrate fusion arising as a result of pressure immobilization. It has been suggested that an optimum range of pressure is required to unite cranial bones in contact with one another.[12] If this concept is correct, then the range of force used in the present experiments must have been optimal to produce bony union.

Two factors appear necessary for inhibition of sutural growth. First, an adequate force, and secondly, abutment and immobilization of bones. This may have implications in the treatment of Class II malocclusion by means of headgear traction. That growth can sometimes be deviated or inhibited is likely, for headgear traction has been demonstrated to induce changes in the relationship of the maxilla to the skull. The direction of force application may be a critical factor in this form of treatment and attention should be directed to the application of force at right angles to the maxillary sutures interdigitating with the skull in order to avoid a sliding or shearing movement of bones across one another. Furthermore, if force application is intermittent, it is likely that sutural fusion may not occur but resorption will eventuate instead. Further investigation of this aspect of force application is required.

In contrast to the rapid movement of bones at sutures, little change occurs when either a compressive or tensile force is applied to cartilaginous growth sites. This is consistent with previous work demonstrating resistance of cartilage to abnormal stress; for example, when the metaphysis and the epiphysis are stapled together to inhibit growth, wires sometimes break as elongation continues.[13,14] Indeed, in young calves, forces of the order of 500-560 lb are required to inhibit endochondral growth.[15] However, prolonged and abnormal forces are known to induce distortion of endochondral growth sites. In the present experiments this occurred with both increased compressive and tensile stress applications. The slight growth inhibition observed probably resulted from damage to the endochondral growth sites during insertion of springs, while the lateral deviation could be attributed to remodelling of bone in the direction of abnormal mechanical stress. Similar general conclusions were reached by Trueta and Trias[16] following deformation induced by compression and fixation of the knee joints in rabbits.

The present experiments demonstrate that while cartilaginous proliferation is relatively unaffected by abnormal stresses, the underlying bone remodels to permit adaption to changing stresses. This provides support for the contention that with the forces exerted by orthodontic appliances, the cartilaginous condyle is not likely to be affected, but that over long periods of time changes in the angulation of the head and neck of the bone may occur as a result of the normal processes of remodeling of bone adapting to altered stress.

The different response to force application at sutural and endochondral growth sites accounts for the ease with which certain growth anomalies can be created by perverted stress, and also for the difficulty of correcting others by the use of mechanical forces, particularly those used in orthodontics and orthopaedics. Although it has been suggested that bone growth and architecture are adapted largely to pressure or tension[17,18] or mechanical function,[19] it is likely that the optimum degree of force required for alteration of growth patterns will be different for different tissues and depend upon numerous factors such as composition, blood supply and nature of adjoining structures. More detailed studies of the mechanism of tissue changes under stress may help to elucidate the importance of mechanical factors in bone growth and how they may be used to divert growth in the correction of malocclusion.

Summary

A method of using helical torsion springs to apply continuous mechanical stresses of known magnitude to bones has been developed. This has been used to demonstrate bone changes in growing guinea pigs following application of abnormal tensile and compressive forces. Tensile stress of the order of 150 gm applied directly to bone tissue induced little change. A comparable force applied to the two parietal bones across the midsagittal suture induced rapid lateral movement of bones associated with a widening of the suture. A similar stress applied to an endochondral growth site slightly decreased the rate and changed the direction of growth.

In contrast to tensile stress, compressive forces applied across the midsagittal suture induced bones to slide past one another or to abut, obliterating the suture. Abutment of bones was associated with fusion of the suture within forty days inhibiting lateral growth of the vertex of the cranium. Compressive stress applied across the epiphyseal plate of the tibia slightly reduced the rate, and altered the direction of growth of the bone.

This study demonstrates that the degree of bone change induced by an abnormal mechanical stress is determined not only by the direction of applied force but also by the nature of the growth sites affected. Further work is required to demonstrate the precise nature of tissue changes associated with abnormal mechanical stress application.

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