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BONE-MARROW PRESSURE AND BONE STRENGTH

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The pattern of bone-marrow pressure changes differed with the mode of stress application. Intra-medullary pressure remained steady during most of the slow loading. During rapid dynamic loading, however, a slight rise in intra-medullary pressure was observed. Contraction of the femoral muscles also resulted in a greater bone-marrow pressure increase. A correlation of 0.98 ($P < 0.001$) between stimulus strength and intra-medullary pressure was obtained. The rise in intra-medullary pressure with femoral muscle contraction is suggested to have a possible role under extreme stresses in living conditions.

Key words: bone-marrow pressure; hydraulic strengthening of bones; nerve stimulation and intra-medullary pressure; muscle contraction and bone-marrow pressure

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Roaf (1960) claimed that when spinal compression occurred the vertebral end plate bulged and blood was forced out of the cancellous bone of the vertebral body into the perivertebral sinuses, and that this was the normal energy dissipating mechanism on compression.

Virgin (1951), Hirsch (1951), Brown et al. (1957), Hardy et al. (1958), Roaf (1960), Eie (1966), and Smith (1969) have shown that lumbar vertebral bodies and end plates fail during *in vitro* experiments when pressures lower than those calculated by Bradford & Spurling (1945), Bartelink (1957), and Morris et al. (1961) for *in vivo* situations are applied. Frost (1964) and McPherson & Juhasz (1965) have suggested that bones may be considerably strengthened hydraulically by the intra-medullary fluid pressure.

Swanson & Freeman (1966) rejected this probability on the basis of results from compression experiments performed on dried and defatted femora. However, resistance to stress of bone *in vivo* may be different from that in *in vitro* situations, due to the effects of vessel occlusion and muscle contraction demonstrated by Herzig & Root (1959), Azuma (1964), and McPherson & Juhasz (1965). Shaw (1963) showed that, in 90 out of 100 experiments, the intra-medullary blood flow was directly related to the marrow pressure in the hind limb of cats. This finding was confirmed by Azuma (1964) for dogs.

The present experiments were undertaken to determine the effects of slow and fast loading of the femur on the femoral marrow pressure in rats. The effect of graded contractions of the overlying quadriceps muscle on femoral marrow pressure was also investigated.

APPARATUS

The output of the duly calibrated pressure transducer (SE 4–81) from bone-marrow was fed to the d.c. amplifier via the carrier amplifier (SE 4912) of the Electro-Medical Multichannel

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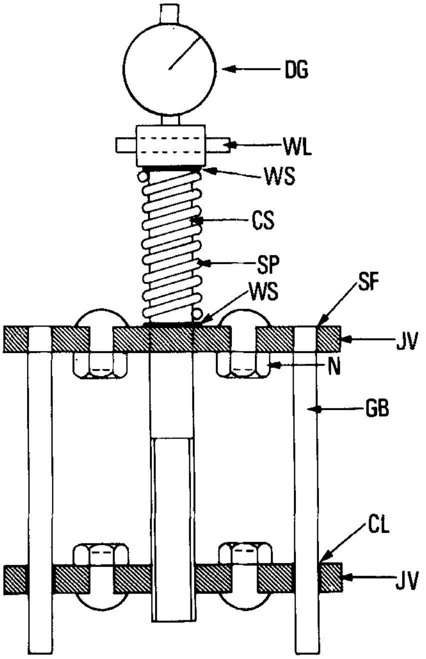

Figure 1. Compression device. DG – Dial gauge, WL – winding lever, WS – washer, CS – Central loading screw, SP – spring, SF – Shrink fit, JV – Jaw of the vice, N – Nut, GB – Guide bar, and CL – clearance.

Amplifier System (SE 4001). The amplified signals were recorded by means of a UV recorder (SE 3006/DL) and were also fed to a display oscilloscope. The transient response of the measuring and recording system was 0.16 seconds for a step function of 13.3 kPa (100 mmHg). A constant intensity stimulator (SRI, 6060) was used to produce square wave electrical stimuli of 1 ms duration and 50 Hz between 0.5 V to 5.0 V.

The compression device (Figure 1) enabled measurable and variable loading to be applied to the rat's femur. It also acted as a firm holding mechanism for the greater trochanter and medial condyle of the femur, maintaining the bone in a vertical position throughout the experiment. A flat jawed vice with a central loading screw and two guide bars was used. Matching bolts were screwed on corresponding positions in the two jaws of the vice with half their recesses available to accommodate the ends of the femur. Enough clearance was available in the top plate around the central loading screw so that the top plate was able to slide down freely with guide bars attached to it guiding a vertical motion. The central loading screw was fitted with a winding lever at its upper end. A compression spring (L.S. 800/40) was placed between the washer above the top jaw of the vice and the washer at the upper end of the loading screw. The spring had twelve active coils with spring constant 5247.2 N/m (5.3 kg/cm). A dial gauge, displaying the amount of compression, was fixed at the top of the winding lever.

MATERIALS AND METHODS

Eighteen male albino rats, under intraperitoneal nembutal anaesthesia, were used. Of these, six were subjected to slow compression, six to fast compression, and six to femoral nerve stimulation.

In animals to be subjected to loading experiments, a transverse incision was made across the knee joint of the left leg. This incision was extended proximally on the lateral side of the thigh as far as the hip. The skin was reflected and the muscles were separated longitudinally along the fascia between gracilis and adductor magnus on one side and sartorius and adductor longus on the other. Damage to the blood vessels was carefully avoided. The exposed muscles were covered with cotton wool soaked in warm saline. The separation of the muscles was carried out up to the hip joint, and the head of the femur carefully dislocated from the acetabulum. At the distal end, the patella was severed from the condyloid surface of the tibia and reflected upward. A hole of 0.00015 m (0.15 mm) diameter was drilled into the medullary cavity from the mid-point of the mid-femoral shaft, and particles of bone were rapidly removed by saline lavage. A blunted hypodermic needle of 0.00079 m (0.79 mm) external diameter filled with saline containing heparin and connected to the pressure transducer was twisted in the hole drilled in the femoral shaft to make a tight fitting connection. The bone was then held by the greater trochanter and condyle between the jaws of the vice in the nut holes. The central loading screw was driven in until the bone was firmly gripped. The dial gauge was subsequently adjusted to zero on the top of the central loading screw.

In slow loading experiments the compression was applied over a period of 1 minute to gaps of 1.36 kg from 0 to 12.25 kg by slow rotation of the central loading screw. Each applied load was maintained for 2 minutes to allow for any gradual pressure build-up. Any rise in the marrow pressure following loading was permitted to settle before the next incremental load was applied. During fast loading similar loads were applied but the process of each loading was completed within 2 seconds. After each step of loading there was an observational pause of 2 minutes. A sudden loading omitting two and more of the intermediate steps was also tried.

In those animals to be subjected to electrical

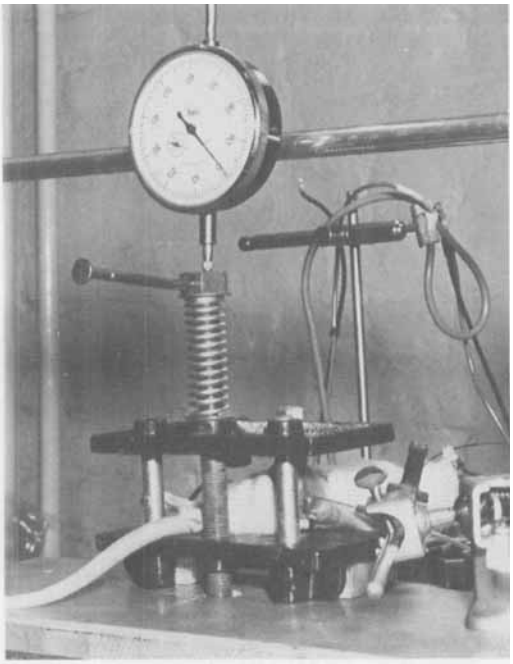

Figure 2. Photograph showing the femur of an anaesthetised rat gripped in the compression device.

stimulation to produce contraction of the overlying muscles a transverse incision along the knee joint of the left leg was prolonged on the medial side. The femoral nerve was traced up to the groin and divided as proximally as possible. The patella was separated from the tibia, reflected upward and a hole drilled in the longitudinal axis of the femur through the condyle. The knee joint was flushed with warm saline and the needle feeding the transducer was inserted deep into the bone marrow. All muscles overlying the bone were thus undisturbed. The cut distal end of the femoral nerve was placed on the bipolar electrode of the stimulator (Figure 2).

RESULTS

The normal resting range of bone-marrow pressure in all the rats studied in the present series varied from 1.07 to 2.40 kPa (8 to 18 mmHg) [mean resting pressure 1.65 kPa (12.4 mmHg), standard error of the mean 0.08 kPa (0.6 mmHg)]. The most frequently observed values were between 1.6 kPa to 1.87 kPa (12 to 14 mmHg). The marrow pressure tended to vary within the range of 0.267 kPa (± 2 mmHg) under resting conditions.

Slow loading

The bone-marrow pressure did not alter either during the period of loading or on completion of the process and maintenance of the load. In higher ranges of loading sometimes an obvious fluctuation of bone-marrow pressure within the normal pressure variation range was observed.

Fast loading

During fast loading, bone-marrow pressure variations were normal within the range of 0 to 2.7 kg. Beyond this level as the loads were swiftly applied, sudden pressure changes were observed, these being more pronounced if the loading omitted two of the intermediate steps. A rise of 2 kPa (15 mmHg) was observed when the compression was raised from 4 kg to 12.25 kg. Generally, a higher magnitude of compression engendered greater increases in the intra-medullary pressure.

Contraction of the overlying muscles

Stimulation of the femoral nerve, causing contraction of the quadriceps muscles resulted in a considerable rise in bone-marrow pressure (Figures 3 and 4). There was a progressive increase in bone-marrow pressure with each increment in stimulus strength. A maximum pressure rise of 8 kPa (60 mmHg) was recorded with 5 V stimulation. A high degree of correlation between stimulus strength and intra-medullary

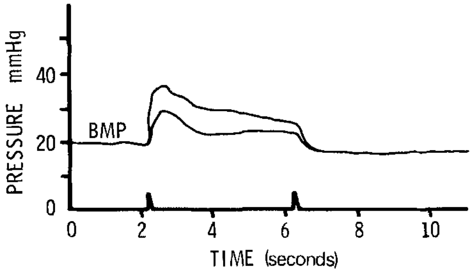

Figure 3. Trace showing the bone-marrow pressure (BMP) during contraction of the overlying muscle due to electrical stimulation of 1.0 volt.

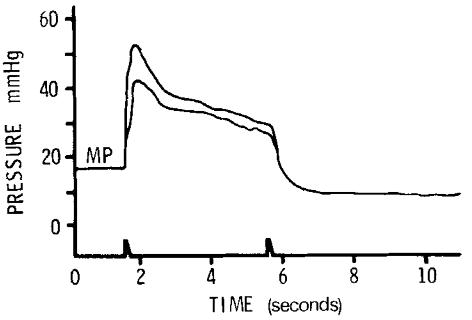

Figure 4. Trace showing the bone-marrow pressure (BMP) during contraction of the overlying muscle due to electrical stimulation of 3.0 volts.

pressure ($r = 0.98$, $P < 0.001$) was found within the range of experimental setting (Figure 5).

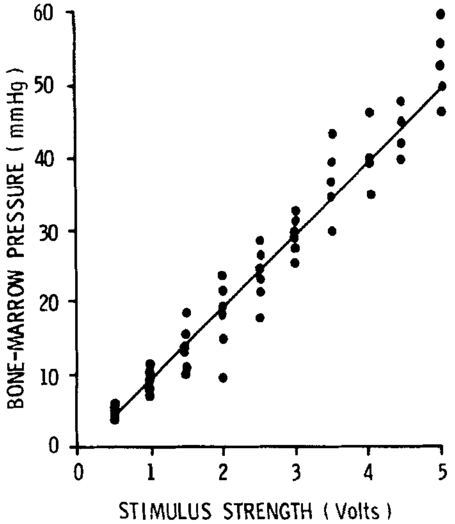

Figure 5. Graph showing femoral intra-medullary pressure with increasing stimulus strength.

DISCUSSION

Following their compression experiments on dried and defatted femora, Swanson & Freeman (1966) concluded that bones are not hydraulically strengthened. The present study has shown that mere compression of bone, through either slow or fast loading, produced only small changes in the intra-medullary pressure and that the contraction of overlying muscles produced greater increases. In life, excessive compression stress tends to cause bone fracture which can be resisted by the sudden and significant rise of marrow pressure caused by simultaneous contraction of the overlying muscles. Elimination of this vital factor renders the conclusion of Swanson & Freeman (1966) unacceptable.

The mechanism of rise of intra-medullary pressure during electrical stimulation of the cut distal end of the femoral nerve was compression and closure of the venous drainage channels from the bone when the overlying muscles were in a state of contraction. The large magnitude of the rise in intra-medullary pressure [8 kPa (60 mmHg)] recorded in a small animal is thought considerable and suggested to provide hydraulic strengthening. However, it is suggested that this factor is unlikely to be of major significance in normal stresses encountered in life. Under excessive compression, on the other hand, when *in vivo* the intact bone is reaching its threshold strength, the raised fluid pressure may play an important role. It is recognised that bone as a tissue may not exhibit this property.

A vasoconstrictor function has been attributed by Drinker & Drinker (1916) to the sympathetic fibres which richly innervate the arterioles of bone marrow. Constriction of these arterioles produced either by electrical stimulation or drugs results in reduction of marrow blood-flow and pressure (Herzig & Root 1959, Azuma 1964, and McPherson & Juhasz 1965). Stimulation of the cut distal end of the femoral nerve does not affect the bone-marrow pressure or blood flow if contraction of the overlying muscles is prevented (Shaw 1963) It is, therefore, clear that the above observation, reported by Shaw (1963), was due to lack of sympathetic activity. Since the electrical stimulation employed in the current study was similar to that of Shaw (1963), it is considered that the marrow pressure changes observed were due to vessel occlusion (Herzig & Root 1959, Shaw 1963, Azuma 1964, and McPherson & Juhasz 1965) caused by muscle contraction. The results were not influenced by sympathetic fibre activity. Indeed, sympathetic vasoconstrictor action will only tend to diminish the magnitude of the pressure increase recorded. In spite of such a contradictory influence, there was a large marrow pressure rise. Thus, one can safely suggest a greater hydraulic support in life as no sympathetic activity is evoked during voluntary contraction of muscles.

The results (Figures 3 and 4) show an immediate rise in intra-medullary pressure on contraction of the quadriceps muscles. This rise in marrow pressure was followed by a slow reduction during the remaining time for which muscle contraction was sustained. This pressure reduction may result from the ejection of venous blood from the femur through vascular openings around the femoral neck. As the femoral nerve was cut at the level of the inguinal ligament and the nerve supply to ilio-psoas and muscles in the region of the femoral neck arise proximal to this level, it is presumed that muscles in that area remained in a relaxed state in these experiments and did not exert any force to close off venous channels. It is possible that in a real life situation a contraction of the ilio-psoas muscles, simultaneously with the quadriceps group, would reduce the outflow through these channels, thereby enhancing the hydraulic strengthening effect.

Although the present experiments measured intra-medullary pressure changes in the femur, it has been shown by Yamamoto (1925), Sabin & Doan (1927–1928), and Foa (1943) that in spite of the diverse distribution of the marrow in different bones in the body, its behaviour and physiology is essentially similar in all situations.

With presently available techniques direct experimentation on vertebral bodies under *in vivo* conditions presents many problems. Though no experimental proof has been furnished, it would appear reasonable for the findings from the present study to be applied to the vertebrae. This suggestion gains further support from the observations made by Batson (1940, 1957), Willis (1949), and Smith & Stephens (1968).

Batson (1940, 1957) has shown large venous channels emerging from the vertebrae and entering the erector spinae muscles. Willis (1949) has described very large venous foraminae emerging from the vertebral bodies. Contraction of the erector spinae muscles would be expected to produce a considerable increase in the intra-medullary pressure within the vertebral bodies. The large cross-sectional area of human vertebral bodies will tend to further magnify the effect of hydraulic support, when such a rise in pressure occurs.

Smith & Stephen (1968) have shown that vertebral bodies compressed *in vitro* undergo considerable shortening, although no such shortening has been observed in life. During trunk manoeuvres, when the muscles are actively contracting and the spine is simultaneously subjected to a large compression, the fluid content of the vertebral body will tend not to be allowed to escape. Therefore, it is possible that these two stresses may have a cumulative effect on the pressure changes of spinal marrow.

Davis (1956 and 1959), Bartelink (1957), and Morris et al. (1961), suggested that a raised intra-abdominal pressure produced by a contraction of the abdominal wall muscles helps to relieve compression forces on the lumbar vertebra. A rise in intra-abdominal pressure would tend to reduce venous outflow from the vertebral bodies; further reduction in outflow is likely when the overlying psoas muscles are in a stage of contraction. Thus, it is suggested that anatomical characteristics and physiological patterns are conducive to and compatible with the hydraulic mechanism of strengthening of bones. Such a mechanism has a significant role in protecting bones under extreme stresses.

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