J. Physiol. (1984), **357**, *pp.* 417–439
With 12 *text-figures*
Printed in Great Britain

PRESSURE–VOLUME RELATIONSHIPS AND ELASTANCE IN THE KNEE JOINT OF THE DOG

BY *SYDNEY NADE AND PETA J. NEWBOLD

From the Department of Surgery (Orthopaedic Surgery), University of Western Australia, Queen Elizabeth II Medical Centre, Nedlands, Western Australia 6009

(*Received 26 August 1983*)

SUMMARY

1. This study has investigated changes in intra-articular hydrostatic pressure in the knee joints of normal dogs in response to continuous and stepwise infusions of fluids. The relationship between pressure and volume in the joint was examined over the pressure range of -8 to $+50$ mmHg, and also at much higher pressures often associated with joint disease or injury. The effects of joint angle and dog weight on the pressure–volume relationship and on elastance of the dogs' knees were also examined.

2. With liquid paraffin B.P. the pressure was found to increase more with each unit volume infused at subatmospheric pressures than at pressures around atmospheric, and increased more again at higher pressures. The pressure–volume curve with saline infusions was affected by egress of fluid from the joint at supra-atmospheric pressure. Above $+5$ mmHg the rise in pressure per unit volume infused was less than that for paraffin at the same volume.

3. Elastance and compliance of the normal joint capsule were calculated from the pressure–volume data. Elastance was high at subatmospheric pressures, decreased rapidly as atmospheric pressure was approached and rose as a linear function of pressure above 12 mmHg.

4. The biphasic shape of the elastance–pressure curve is discussed, and explanations for the shape are suggested.

5. After intra-articular pressure in the knee was raised by infusion of paraffin oil the joint was moved through the range of positions from 125 deg extension to 50 deg flexion. Intra-articular pressure did not change across the range 125–110 deg. However, increasing the angle of flexion from 110 to 50 deg resulted in a rise in pressure which became steeper for each volume increment.

6. Increasing intra-articular fluid volume caused a decrease in the total range of movement of the joint.

7. The pressure–volume curves measured at extended angles of 110, 125 and 140 deg, where the starting pressures were subatmospheric, were the same. At flexed joint positions of 80 and 50 deg, where the starting pressures were supra-atmospheric, the pressure–volume curves became steeper with greater flexion.

---

* Authors names are in alphabetical order.

8. Elastance of the joint tissues increased with flexion. The elastance at each joint angle depended also on the volume or pressure.

9. Significant differences were found to exist between pressure–volume curves for three groups of animals of different weight. Curves were steeper in small animals.

10. Acrylic casts of the knee joint space were constructed at 90 and 40 deg of flexion to demonstrate channels of communication between anterior and posterior regions. The anterior compartment provided two-thirds of the total surface area.

INTRODUCTION

The prime functions of synovial fluid are lubrication and nutrition of joints. Two of the major clinical manifestations of articular pathology are effusion and 'stiffness' of the joint. Stiffness of the joint implies a change in the elastance of the joint tissues. The formation of an effusion implies that there has been an excessive net inflow of fluid into the joint, and the maintenance of the effusion indicates an aberration in synovial fluid dynamics. High intra-articular pressures and fluid volumes in abnormal joints may result in limitation of movement of the joint, changes in viscosity and composition of the synovial fluid, instability of the joint, and may also inhibit synovial blood flow thus impairing the supply of nutrients into the joint. It is impossible to attempt to answer the question 'Why does a joint effusion form?' in pathological joints without knowing more about the synovial fluid dynamics of normal joints.

It is accepted that synovial fluid is essentially an ultrafiltrate of plasma, added to by secretions from synovial lining cells. The net movement of fluid is therefore from capillaries to interstitial space within the synovium, and from there to the joint cavity, lymphatic capillaries or extrasynovial interstitial space. Movement of fluid between these spaces is controlled by numerous factors including arterial and venous pressure which govern mean capillary pressure in the synovial microcirculation, oncotic pressure and viscosity of the fluids, lymphatics of the capsule, and hydrostatic pressure of joint fluid. The latter depends on volume, passive tension of periarticular tissues, muscle contraction, the position of the joint, the compliance of the joint capsule, the stress relaxation or creep of the joint capsule, hysteresis effects, and the range and rate of joint movement. A recent review by Levick (1983) has shown how some of the factors in the above list interrelate.

Because intra-articular hydrostatic pressure at a given volume of fluid depends on wall stress, the relationships between intra-articular pressure and volume provide valuable information regarding the biomechanical properties of the joint capsular tissues, in particular their elastance and compliance. Compliance of these tissues can be represented by the change in volume per unit change in pressure ($\mathrm{d}V/\mathrm{d}P$) and its converse, elastance, as the change in pressure per unit change in volume ($\mathrm{d}P/\mathrm{d}V$).

Pressure–volume relationships have been described in studies on abnormal human knees carried out by Caughey & Bywaters (1963), Jayson & Dixon (1970*a*), Steer, Jayson, Dixon & Beighton (1971) and Myers and Palmer (1972), and in animals by McCarty, Phelps & Pyenson (1966). O'Driscoll, Kumar & Salter (1983), Knight & Levick (1981, 1982*a*,*b*, 1983) and Jayson & Dixon (1970*c*) have investigated several aspects of the relationship between pressure and volume in the normal knee joints of rabbits and man. An interesting finding by Knight & Levick (1982*b*) was the existence of anatomically continuous but hydraulically distinct compartments within the knee joints of rabbits. This became apparent when they discovered differences in the shape of the pressure–volume curve dependent on the location of the infusion and recording cannulae within the joint space. This type of physiological compartmentation has not previously been looked for in other species.

Both trans-synovial fluid exchange and joint elastance appear to be especially affected by intra-articular pressure during flexion of the joint, when pressures are greatly increased. Intra-articular pressures in the dog's knee joint were found to range from −17 (mean −6·4) to +50 mmHg (mean +28·2) over a natural range of flexion and extension (Nade & Newbold, 1983). Jayson & Dixon (1970*c*) also studied the effects of movement on intra-articular pressure, and other studies (Eyring & Murray, 1964; Levick, 1979) have indicated that flexion of a joint not only elevates intra-articular pressure but also increases the elastance. Another factor which might be expected to affect elastance is the size of the joint. McCarty *et al.* (1966), in their experiments with dogs, suggested that the size of the knee joint affected intra-articular pressure. When body weight was used as an indicator of joint size, it was not found to correlate well with either intra-articular pressures or volumes of effusate in the knees of human subjects (Jayson & Dixon, 1970*a*).

The present study is devoted to the behaviour of normal tissues during distension of the dog joint in response to changes in intra-articular fluid volumes and to change in the nature of the fluid. In particular, it examines the relationship between pressure and volume at both sub- and supra-atmospheric intra-articular pressure levels and discusses the origin and functional significance of this relationship. From the static studies – with the joint in one position – elastance and compliance of the periarticular tissues has been determined. In addition, the effects of intra-articular pressures resulting from different joint angles on the elastance of the normal knee were examined in the dog. The influence of dog weight on the pressure–volume curve was determined by using animal groups of different body weights and sizes, with different-sized joints. Finally, the compartments in the dog's knee were defined by making casts of the joint at different angles, and the synovial surface area within the various parts of the joint was measured.

METHODS

The preparation of the animals for experimentation has been described previously (Nade & Newbold, 1983). Mongrel dogs weighing between 10 and 21 kg were anaesthetized with pentobarbitone (30 mg kg^{-1}) and maintained, using a CIG Midget 3 anaesthetic machine, by inhalation of an oxygen/nitrous oxide/halothane mixture for the duration of each experiment. The animals were supine with the thighs attached to metal scaffolding in a vertical position with respect to the body. The legs were supported by a horizontal bar set in a position at which the intra-articular pressure in the knee would be lowest, a joint angle of approximately 125 deg. The joint angle was adjusted between infusions by moving a horizontal bar, which rested under the legs of the animal, attached to and controlled by a small-animal servo-manipulator (Mills, Newbold & Nade, 1982).

Cannulation of the knee joints

Two 18 gauge inextensible fluid-filled Teflon cannulae, with small perforations around the tip, were inserted into the infrapatellar region of each joint (Nade & Newbold, 1983). Fig. 1 illustrates the fluid-infusion and pressure-recording system. One cannula (cannula 1) was connected through fluid-filled tubing to a pressure transducer (Statham Model P23DC) via a three-way stopcock (1). The second cannula (2) was connected directly on to a two-way stopcock (2), positioned immediately adjacent to the knee joint. The stopcock was connected through inextensible tubing to a glass syringe set into an automatic infusion pump (Harvard Apparatus Compact Infusion Pump). The correct positioning of the cannulae tips in the joints was confirmed by dissection at the end of each experiment. The other knee was cannulated in the same manner. The maximum error which could be introduced, due to leakage or distension of the infusion and recording apparatus (including tubing, cannulae, connections and taps) was measured to be 1 mmHg h^{-1} under a constant pressure of 50 mmHg. Aggregate apparatus compliance was 0·16 μl $mmHg^{-1}$ between 0 and 126 mmHg. During cannulation the cannula was only open to the atmosphere for approximately 1 s. Base-line drift of the recorder was less than 2 mmHg h^{-1}. This was monitored and corrected, when necessary, at regular intervals throughout the experiment.

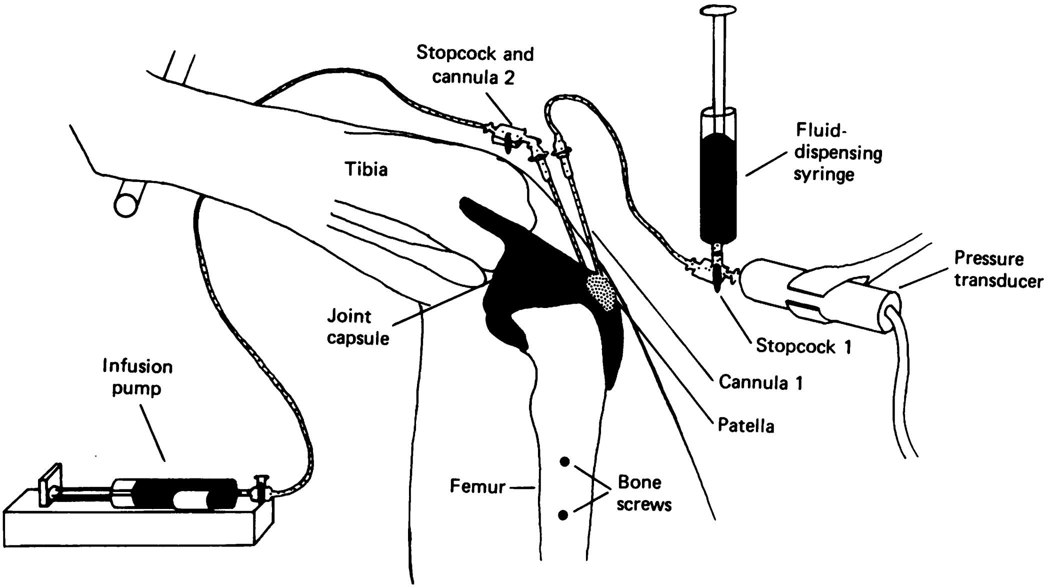

Fig. 1. System for infusing or perfusing the knee joint with fluid and for recording intra-articular hydrostatic pressure.

Fluid-infusion system

Before each controlled infusion, in order to ensure that the joint contained only the same fluid that was to be infused during the experiment, the joint was flushed with this fluid. This was done by perfusing into stopcock 1 while it was closed off from the transducer, and allowing the fluid to flow out of stopcock 2. Intra-articular pressure was adjusted to its original and natural level either by injecting more fluid (to increase pressure), or by using gentle manual pressure on the joint to expel fluid from the joint, or very slowly aspirating fluid from the joint through cannula and stopcock 2 (to reduce pressure). This pressure (usually subatmospheric) was recorded until stable over 5–10 min, after which the study was commenced by controlled infusion of fluid through cannula 2, either in a stepwise manner or continuously from the infusion pump.

Experimental protocols

Pressure–volume relationships in normal knees. Liquid paraffin oil B.P. or physiological saline was infused continuously at 444 μl min^{-1} for 20–25 min, or occasionally 90 min. Infusions were begun with the intra-articular pressure adjusted to below atmospheric pressure. In most cases only one infusion per joint was carried out. When repeated infusions were made in the same joint an interval of up to 20 min was left between infusions to allow the capsular tissues to recover from any effects of stretch caused by the previous infusion. The interval was also used to ensure that the joint had not been irritated by the infusions and was forming its own effusion. This would have been detected by a rise in intra-articular pressure during base-line recording.

The results from infusions with saline were compared with those using non-permeant paraffin oil, in order to obtain an estimate of the volume of fluid lost from the joint at various intra-articular hydrostatic pressures. In some cases saline and paraffin curves were determined in opposite joints of the same dog. The synovial tissues are permeable to saline solutions (Palmer & Myers, 1968; Levick, 1979; and Knight & Levick, 1982*a*) and the high pressures caused by the infusion of this fluid increase trans-synovial fluid movement.

Intra-articular pressure and joint angle at increased intra-articular fluid volumes. The initial joint angle was 125 deg. A measured volume of paraffin oil was infused and the joint was moved successively through increasing degrees of flexion, 110, 80 and 50 deg, while intra-articular pressure was monitored continuously. This procedure was carried out at infused fluid volumes of 0, 0·5, 1·0, 2·0, 3·0, 4·0 and 5·0 ml.

Pressure–volume relationship at different joint angles using continuous delivery of fluid. Pressure–volume curves were obtained at joint angles of 50, 80, 110, 125 and 140 deg during continuous delivery of paraffin oil at a flow of 444 μl min^{-1}.

Pressure–volume relationship in different-sized joints. Animals were grouped according to body weight and a subjective assessment of over-all size and body type. The three groups were 7–10 kg, 10–16 kg and 16–22 kg. With the joints at an angle of 125 deg continuous infusions with paraffin were made at a flow of 444 μl min^{-1}.

Casts of the joint space. An incision was made in the skin of the thigh of freshly killed animals just anteromedially to the suprapatellar pouch of the knee joint. The depth of the incision was increased until the joint space was entered through a cut of approximately 0·5 cm. Sutures were placed around the incision so that it could be closed immediately on withdrawal of the syringe tip.

A soft plastic tip attached to a syringe filled with self-curing dental acrylic (Vertex, Dentimex Zeist, Holland) coloured by Sudan III (George T. Gurr, London) was inserted into the incision. Approximately 10 ml of acrylic was infused into the joint set at 90 deg, and 5 ml into the joint set at 40 deg. The acrylic was injected slowly, with the knee initially flexed so that the posterior compartment of the space in the popliteal region could be filled. The knee was progressively extended while the injection continued slowly until finally the syringe tip was withdrawn as the sutures were tightened to close the incision. The joint was gently manipulated over a very small range, to ensure the acrylic filled all aspects of the joint space. It was then flexed to the 40 or 90 deg position and left to harden. Polymerized casts were dissected out for photography. The casts were left attached to the femur which was cut off from the rest of the animal, dried, and placed in refrigerated storage.

Surface area of synovium. After experimentation the joint capsule and synovium were excised from the knee joint of animals weighing 9, 16 and 21 kg in order to calculate the synovial surface area. These weights correspond to the three weight groups already mentioned. The skin and overlying muscles were cut away and the capsular tissue removed in several pieces from around the bones of the knee. The unstretched tissues were placed on transparent paper, and areas traced onto graph paper and counted. The anatomical location of the various areas was noted.

RESULTS

Pressure–volume relationship

Pressure–volume curves were determined, usually once in each joint, in up to twenty-one joints for paraffin oil and in up to twenty–seven joints for saline. Fig. 2*A* shows that the curves for oil and saline were similar at subatmospheric, atmospheric, and supra-atmospheric pressures below 5 mmHg. Above 5 mmHg the differences in pressure between saline and paraffin at the same infused volume (Fig. 2*B*) were highly significant ($P<0·01$ unpaired *t* test). The mean of the differences

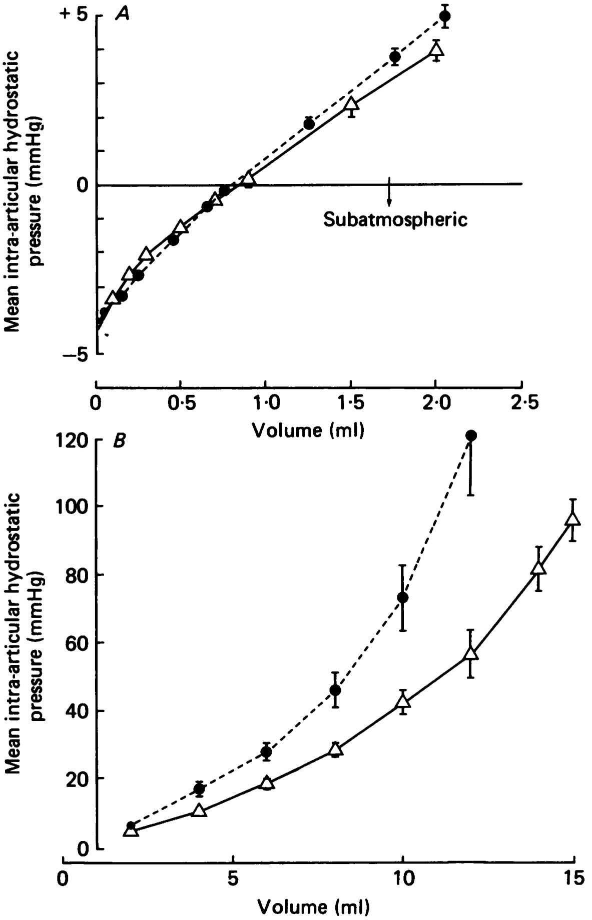

Fig. 2. Mean intra-articular pressures and standard errors of the mean during the infusion of paraffin (●) in up to twenty-one joints and the infusion of saline (△) in up to twenty-seven joints at *A*, negative and low supra-atmospheric pressures and *B*, supra-atmospheric pressures. The curves are continuous from *A* to *B*, but the scales have been adjusted. The relationship between pressure and volume can be seen to differ between paraffin and saline above 5 mmHg.

increased from 1·8 mmHg at 2 ml, to 64·8 mmHg at 12 ml. Pressure for paraffin is plotted against the corresponding pressure for saline at the same infused volume in Fig. 3 (fifty knees). The inset shows the same relationship at low and subatmospheric pressures. The fact that the slope of the relationship above approximately 5 mmHg is greater than 1 (equality) is attributed to synovial permeability to saline. This difference between saline and paraffin curves, representing loss of saline from the joint, was especially evident when paraffin and saline curves were determined in the opposite joints of the same dog and the corresponding pressures measured simultaneously.

The mean pressure–volume relationship, obtained from seven joints which had been selected according to a body weight within the range 15–21 kg and infused with

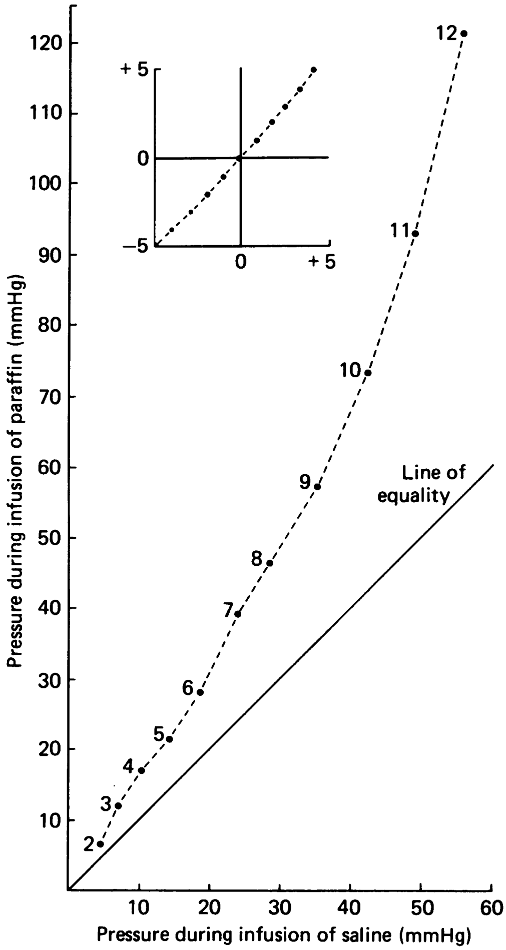

Fig. 3. The mean intra-articular pressure due to infusion of paraffin, shown against the corresponding mean pressure when the same volume of saline was infused. The volume points (●) on the curve indicate the amount infused in millilitres. The inset shows that almost no difference exists in the pressure response to the two fluids at subatmospheric pressures. However, as the infused volume increases the pressure for paraffin becomes increasingly larger than the pressure for saline.

paraffin oil at a constant rate of 444 μl min^{-1} with the joint positions between 90 and 125 deg, was found to be sigmoidal (Fig. 4). The starting pressures were subatmospheric, with a mean of $-5{\cdot}9 \pm 0{\cdot}58$ mmHg ($n = 7$, n = number of animals). At subatmospheric levels, pressure increased more per unit volume than at levels just below or slightly above atmospheric. Atmospheric pressure was usually reached at volumes between 600 and 900 μl. Pressure rise per unit volume increased again at higher pressure levels. Although Fig. 4 shows the pressure–volume relationship for volumes up to 5 ml, some joints were infused with up to 16 ml. Because of the variation in size of joints among animals, even of similar weights, the pressures for a given volume varied, especially at higher pressures.

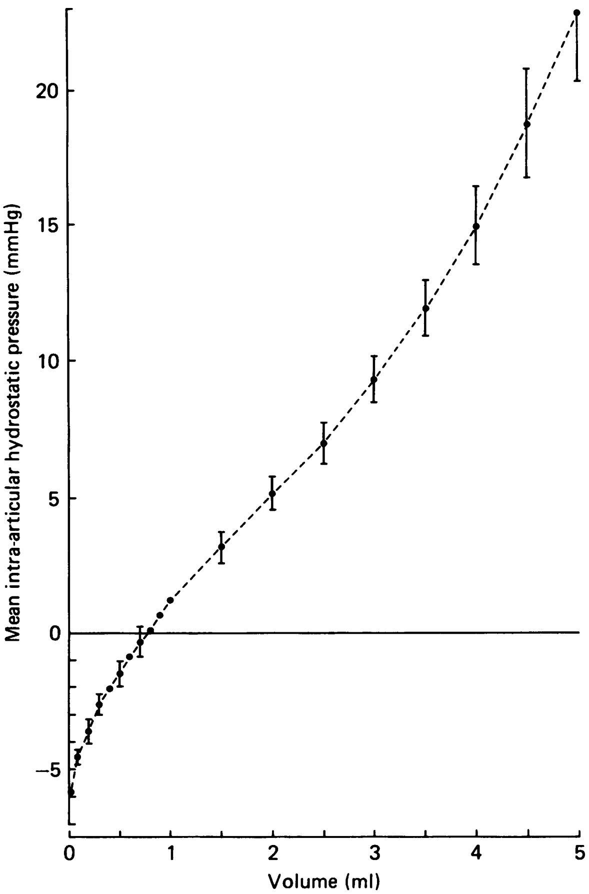

Fig. 4. The mean pressure–volume relationship and standard errors of the mean for seven joints during continuous infusion of paraffin at a constant rate of 444 μl min^{-1} (joint positions between 90 and 125 deg).

Elastance and compliance of the joint tissues

Because of the escape of saline from the joint at supra-atmospheric pressures, only paraffin oil was used for joint elastance experiments. Elastance is a measure of 'stiffness' of the joint. It is calculated from the pressure–volume curve as $\mathrm{d}P/\mathrm{d}V$. Fig. 5*A* shows the elastance of the knee joint of an animal weighing 16 kg, with the knee joint angle at 125 deg, during infusion of paraffin at a constant rate of 444 μl min^{-1}. Elastance was as high as 22 mmHg ml^{-1} at subatmospheric pressures, then declined rapidly as pressures approached atmospheric to a minimum of 3·3 mmHg ml^{-1} at around +4 mmHg. Elastance was low, around 3·3–5 mmHg ml^{-1} at −0·5 to +12 mmHg, then rose slowly to reach 37 mmHg ml^{-1} at +101 mmHg. Total volume infused at this point was 10 ml over 22·5 min. The increase in elastance between +22·5 to +100 mmHg appeared to be a linear function of pressure.

In Fig. 5*B* the same data are presented as change in intra-articular volume per unit change in intra-articular pressure (compliance, reciprocal of elastance). Com-

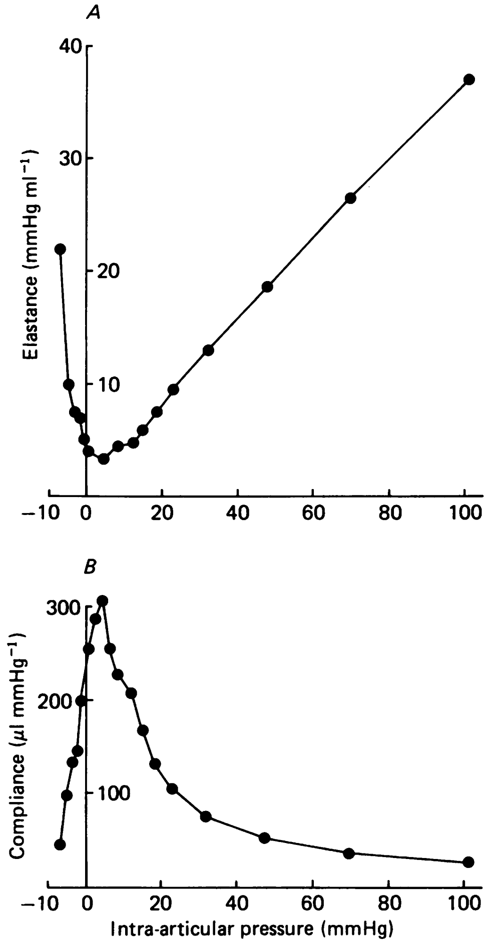

Fig. 5. The elastance (*A*), and compliance (*B*), of the knee joint of an animal weighing 16 kg, with the leg angle at 125 deg, during infusion of paraffin at a constant rate of 444 μl min^{-1}, over a pressure range from -10 to 100 mmHg.

pliance can be considered as the 'stretchiness' of the joint. At pressures less than -5 mmHg compliance was low, and rose rapidly as pressures approached atmospheric. Compliance was high at around atmospheric pressure, and was maximal (300 μl mmHg^{-1}) at $+4$ mmHg. At higher pressures compliance decreased as the capsule was stretched further with the infusion fluid.

The mean elastance with standard error of the mean is shown in Fig. 6 for seven animals of weights 15–21 kg, with leg angles of 90–125 deg, for continuous infusion of paraffin at a constant rate of 444 μl min^{-1}. In all animals elastance was more sensitive to subatmospheric pressures than to supra-atmospheric pressures. The regression slope of mean elastance on subatmospheric pressure ($-1{\cdot}21$ ml^{-1}, $r = -0{\cdot}881$) was greater than that obtained at supra-atmospheric pressures ($+0{\cdot}26$ ml^{-1}, $r = 0{\cdot}997$).

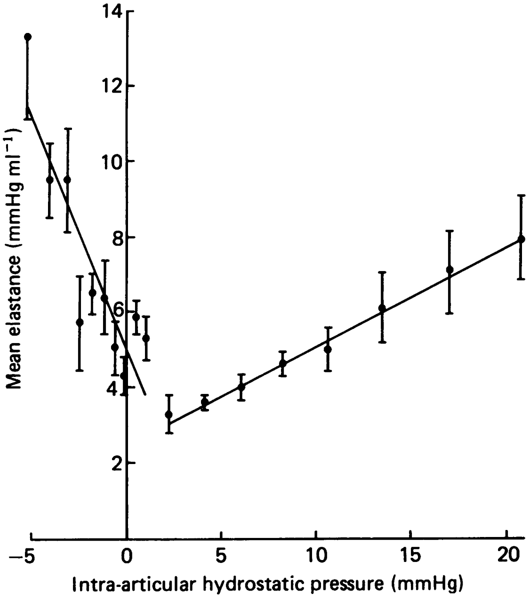

Fig. 6. The mean elastance, with standard error of the mean, for seven animals of weight 15–21 kg, with knee joint angles between 90 and 125 deg, for continuous infusion of paraffin at a constant rate of 444 μl min^{-1}.

The effects of joint angle on pressure at increased intra-articular fluid volume

In Fig. 7 mean pressures and standard errors of the mean are plotted against joint angles of 125, 110, 80 and 50 deg for six joints with infused fluid volumes of 0, 0·5, 1, 2, 3, 4 and 5 ml. There was no difference in pressures, for each volume, between angles 125 deg and 110 deg. Increasing the angle of flexion below 110 deg caused higher pressures and also a steeper rise in pressure per degree flexion. Fig. 8 shows the same phenomenon in a single joint. When intra-articular volume was increased, even small changes of angle had disproportionately large effects on pressures, especially during flexion. The joint was allowed to recover for 35 min after the infusion, until the pressure had decayed to 74 mmHg. To prevent rupture during flexion, the joint was first moved towards extension, although not full extension as pressures also rise considerably at this position when intra-articular fluid volumes are higher than normal. The leg was then moved back through 90 deg to 60 deg flexion, which was as far as it would go without applying too much force: this generated a pressure of 300 mmHg compared with about 10 mmHg at normal volume. The effect of intra-articular fluid volume on pressure was examined in many animals. However, this example (Fig. 8) was chosen to demonstrate the high pressures able to be reached without rupture of the joint.

The effects of angle and dog weight on the pressure–volume relationship and elastance

The effects of joint angle on the pressure–volume relationship were investigated by continuously infusing paraffin into the joints at 444 μl min^{-1} at leg angles of 140 ($n = 6$), 125 ($n = 8$), 110 ($n = 4$), 80 ($n = 6$) and 50 deg ($n = 5$) (Fig. 9). In this experiment the weight of the animal was standardized so that the mean weight was 16·7 kg (S.E. of mean 0·65). The pressure rise per unit volume of fluid (elastance) increased significantly when the joint angle was 80 deg, and even more so at 50 deg flexion. Flexion displaced the whole pressure–volume curve upwards from the volume axis and also made it steeper, increasing the elastance at a given volume.

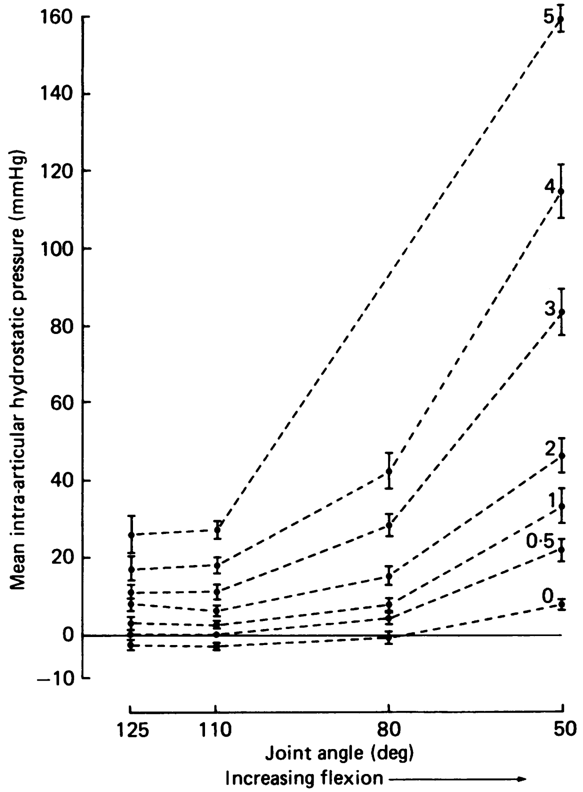

Fig. 7. Mean intra-articular pressures and standard errors of the mean are plotted against joint angles of 125, 110, 80 and 50 deg, for six joints containing intra-articular volumes of paraffin of 0, 0·5, 1·0, 2·0, 3·0, 4·0 and 5·0 ml. After each volume increment the joint was moved successively through increasing positions of flexion while intra-articular pressure was monitored continuously.

The elastance of the periarticular tissues depended on joint angle and on the pressure or volume (Fig. 10). For all volumes elastance increased with the degree of flexion. Elastances at 0·3 and 0·5 ml were high, as were elastances at the much larger volume of 4·0 ml, whereas elastance was relatively low at a volume of 1·5 ml.

When the weights of the dogs were taken into account analysis of variance showed that mean pressures at all infusion volumes above 1 ml were significantly different ($P<0{\cdot}01$) in the three groups of 7–10 kg ($n = 6$), 10–16 kg ($n = 11$) and 16–22 kg ($n = 13$) animals (Fig. 11).

The joint cavity

Shape of the lumen. Fig. 12*A* and *B* are line trace drawings of photographs of the cast of the lateral and distal femoral aspect of the left knee in 40 deg flexion from an animal weighing 19 kg. Fig. 12*C* and *D* are similar drawings of casts of the lateral and distal femoral aspect of the right knee of the same dog, in 90 deg flexion. Very little fluid was contained in the suprapatellar pouch of the joint at 40 deg. The small laterally placed pouch just cranial to the articulation between the fibula and the lateral condyle of the tibia is the extension of the joint space around the head of the extensor digitorum longus muscle and can be seen to extend distally for several centimetres in both joints. The cast of the joint lumen also shows a protrusion posteriorly, lying adjacent to the femoral condyles. In Fig. 12*C* and *D*, the anterior portion at the more extended position contained a considerable volume of acrylic. This includes both the infrapatellar and suprapatellar portion of the joint. In Fig. 12*C*, a channel can be seen to extend laterally towards the area of articulation between the head of the fibula and the lateral condyle of the tibia.

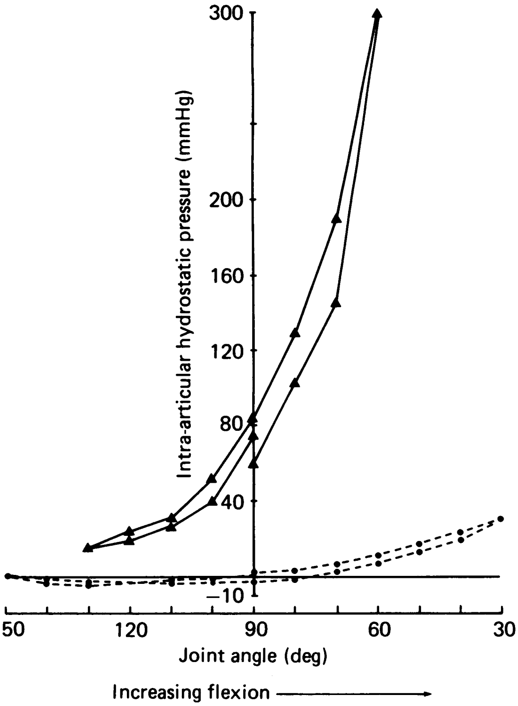

Fig. 8. The effects on intra-articular pressure of flexion and extension in the normal knee (●) and in a knee after it had been infused with 11 ml paraffin oil (▲). In the paraffin-infused knee pressures were increased and the range of movement was limited.

Both Fig. 12*B* and *D* illustrate the channels of communication between the anterior and posterior compartments. The menisci partially divided this portion so that the

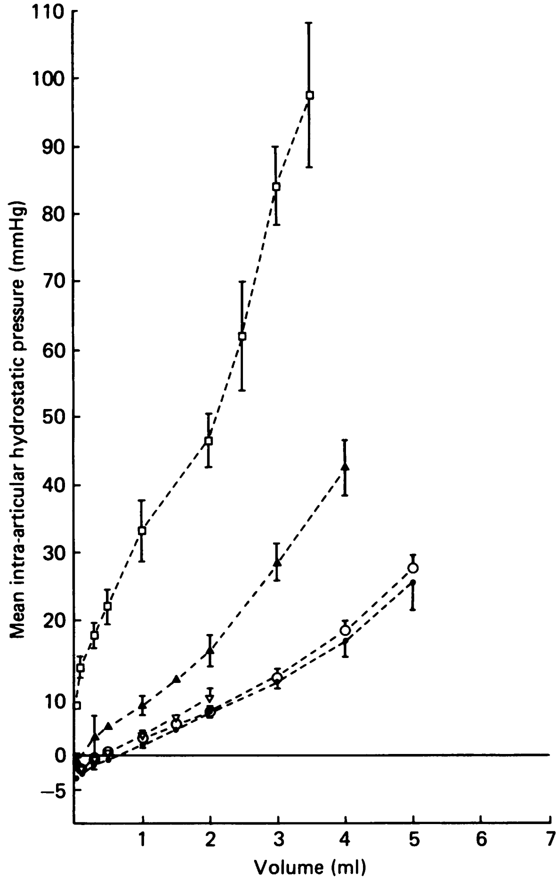

Fig. 9. The relationship between mean intra-articular pressure (with standard errors of the mean) and volume during infusion of paraffin at a constant rate of 444 μl min^{-1} into joints at angles of 140 (●; $n = 6$), 125 (▽; $n = 8$), 110 (○; $n = 4$), 80 (▲; $n = 6$) and 50 deg (□; $n = 5$).

anterior–posterior and medial–lateral sections communicated only around the edges of the menisci and between the cruciate ligaments and femoral condyles.

A small gap in the acrylic can just be seen on the anterior aspects of both knees (Fig. 12*B* and *D*). This is due to the patella in the femoral trochlea with fluid surrounding it on all sides. However, in the joint flexed to 40 deg (Fig. 12*B*) there is a much larger space where the patella had been, and where the capsule had evidently been drawn tightly over the femoral condyles so that fluid was forced to move into the infrapatellar, femorotibial and posterior portions of the lumen.

Surface area

The synovial surface area of the joint capsule in animals weighing 9, 16 and 21 kg was estimated by excision of the synovium of the knee joint. The total areas were estimated to be 27·6, 38·6 and 59·3 cm^2, respectively. The anterior area, including the

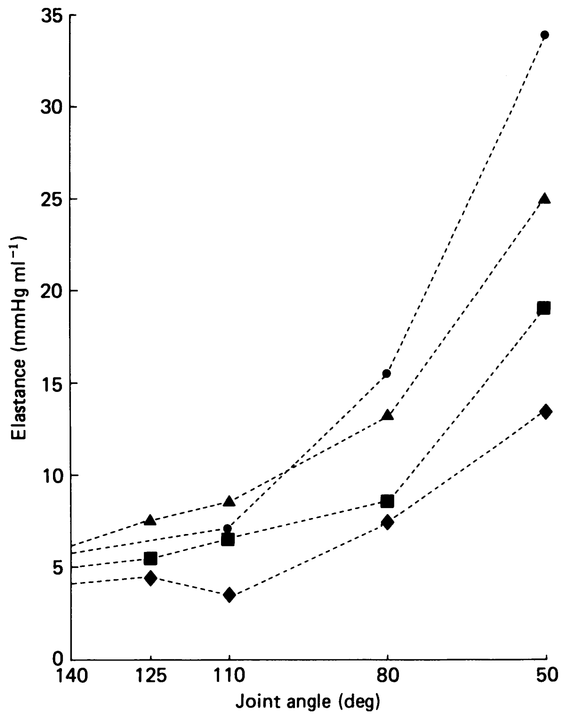

Fig. 10. Elastance and joint angle for intra-articular fluid volumes of 0·3 (▲), 0·5 (■), 1·5 (◆) and 4·0 ml (●).

suprapatellar portion, occupied the largest proportion of the surface. Regardless of the size of dog, the anterior area was about 66 % of the total, while the posterior portion represented only 26 %.

DISCUSSION

Importance of nature of infusate

The relationship between hydrostatic pressure and fluid volume has been examined previously by infusion techniques in the interstitial space (Guyton, 1963; Guyton, Granger & Taylor, 1971), in the pleural cavity (Agostoni, 1972) and, as noted earlier, in both normal and abnormal knees of humans and in animal knee joints. Knight & Levick (1982*a*) pointed out that volumes in previous joint studies were overestimated because of the use of saline to increase the fluid volume. The interstitium and the synovium are highly *permeable* to saline and some leakage of fluid from these spaces would be expected, especially as hydrostatic pressures increased. The passage of paraffin oil B.P. through the synovium is negligible. Palmer & Myers (1968), after infusing human knees with saline, suggested that this fluid was absorbed from the joint when intra-articular pressure was approximately +9 mmHg. Levick (1979) found a difference in pressures for the same volume of infusate between saline and non-permeable paraffin oil in the knees of rabbits. In the present study of dogs' knees, continuous infusions with both saline and paraffin were carried out over intra-articular

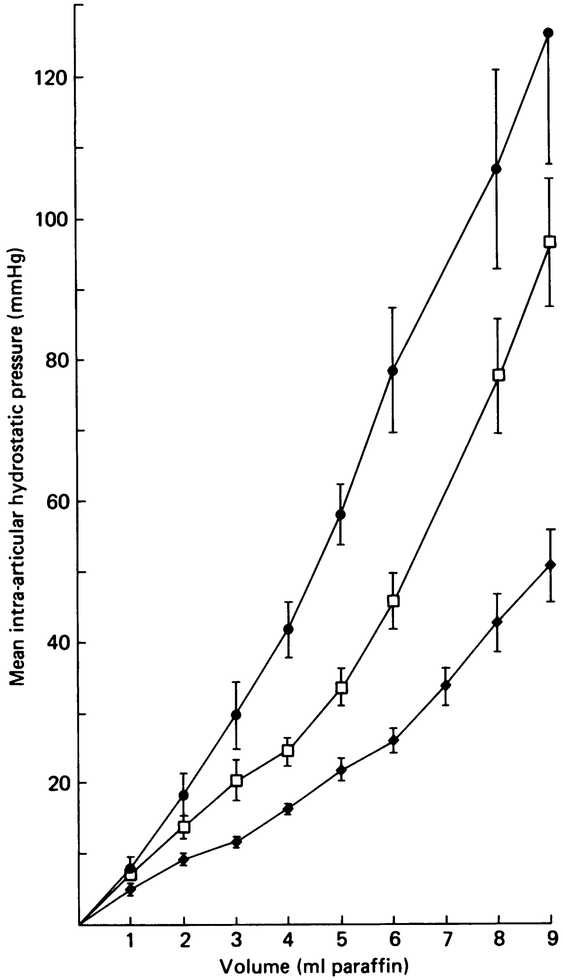

Fig. 11. The mean intra-articular pressures, with standard errors of the mean, for three groups of animals of weight 7–10 kg (●; $n = 6$), 10–16 kg (☐; $n = 11$) and 16–22 kg (◆; $n = 13$), during infusions of paraffin.

pressures ranging from -8 to $+120$ mmHg. The differences in pressures for the same volume increments between saline and paraffin oil were found to be significant above 5 mmHg, and became increasingly large as volume increased.

The results from this study using *continuous infusion* do not show such a large difference between pressures for paraffin oil and saline as do those from the Knight & Levick (1982*a*) study in which interval infusions of a low-viscosity oil were used. In the present study the parameters for infusion into dogs' knees were: continuous rate of infusion at 7·4 μl s^{-1}, with the knee at an angle of 125 deg. In the Knight & Levick study on rabbits the parameters were: 120 μl aliquots infused at a rate of 5 μl s^{-1} every 3 min, with the knee at an angle of 120 deg. Because dogs' knee joints are larger than rabbits', and because of the continuous *versus* interval infusion techniques used in the respective studies, it is difficult to say whether or not the

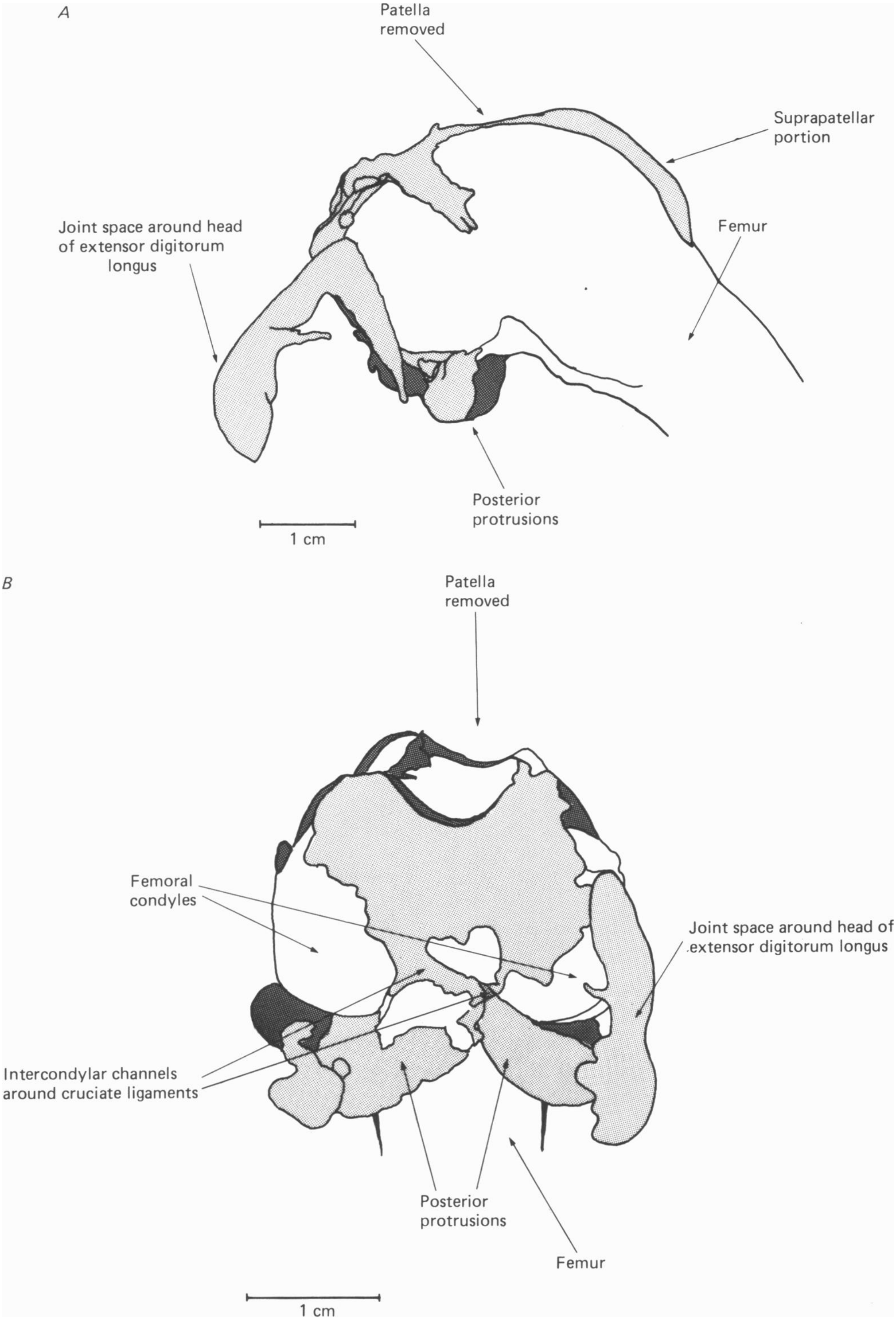

Fig. 12. For legend see opposite.

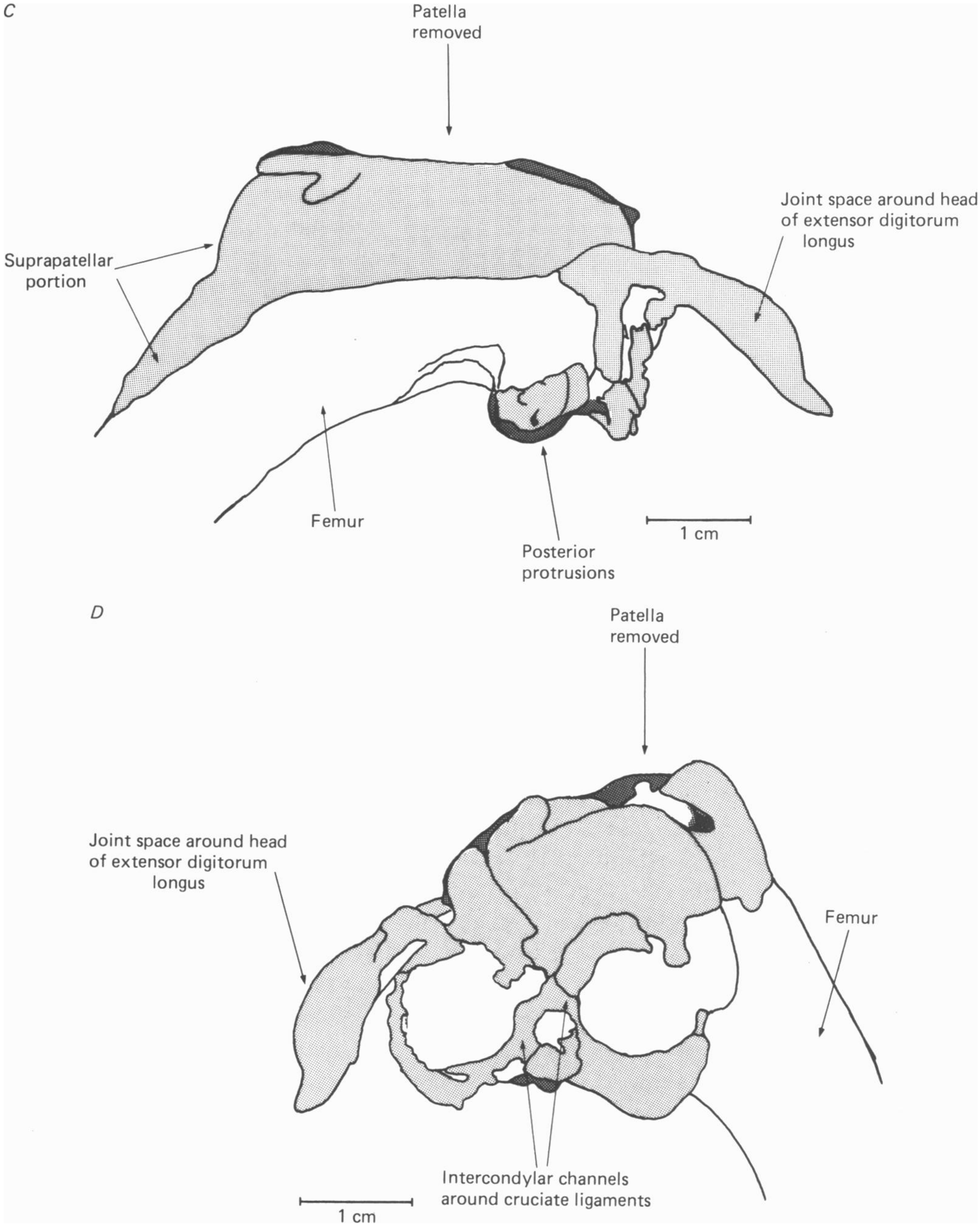

Fig. 12. Acrylic casts of the knee joint cavity. *A*, the lateral aspect of the left knee with the joint at a position of 40 deg flexion. *B*, the distal aspect of the femur of the leg at 40 deg demonstrating the communication between the anterior and posterior compartments of the joint at 40 deg flexion. Note: the patella, patellar ligament, and muscle attachments were removed from around the joint so that the shape of the capsule could be properly determined. The tibia was also removed so that communication between the anterior and posterior portions of the capsule could be seen. *C*, the lateral aspect of the right knee with the joint flexed to 90 deg (tibia, patella and muscles removed). *D*, the distal aspect of the femur demonstrating the communication between the anterior and posterior compartments of the joint at 90 deg flexion (tibia, patella and muscles removed).

differences between the data from these two studies are significant. Both studies show that pressures for the paraffin infusion are higher than for the same volumes of saline infused and indicate that saline is absorbed from the joint. Elastance, however, decays with time (Newbold, 1983; Knight & Levick, 1983). The continuous oil-infusion method estimates 'immediate' elastance, and may result in a slight over-estimation of immediate elastance due to the possibility of a small effect from transient localized pooling of the highly viscous paraffin oil, causing local pressures to be artificially high (see below). The interval-infusing technique used by Knight & Levick measures the smaller delayed elastances and under-estimates immediate elastance.

McCarty *et al.* (1966) reported lower intra-articular pressures during interval infusions of saline into dogs' knees than were recorded in the present study. It is not clear from the work of McCarty *et al.* how long an interval elapsed between infusion and pressure measurement. Leaving an interval of even 2 min after infusion with saline to a pressure of 40 mmHg can result in a drop in pressure of 10–15 mmHg.

Viscosity of the infusate deserves mention here. Paraffin oil B.P. is 26 times more viscous than saline, and must therefore disperse from the immediate site of infusion at a much slower rate. Therefore, the local anterior pressure recorded with the oil could be higher than with an equal, evenly distributed volume of intra-articular saline. However, the dog's knee is large and the central placement of infusion and recording cannulae reduce the probability that dissipation of the fluids within the joint will be significantly inhibited. This makes it unlikely that the difference in pressures between saline and paraffin can be accounted for by viscosity effects alone.

Explanation of shape of pressure–volume curves and joint elastance

The shape of the mean pressure–volume curve resulting from paraffin oil infusions, over the range of $-5{\cdot}9$ to $+23$ mmHg, was sigmoid (Fig. 4). Knight & Levick (1982*a*) found a similar sigmoid pressure–volume relationship with low-viscosity oil in rabbits' knees. Jayson & Dixon (1970*a*) and Myers & Palmer (1972) used saline in human knees, as did McCarty *et al.* (1966) in dogs' knees and O'Driscoll *et al.* (1983) in rabbits' knees. These authors did not measure the pressure–volume relationship at subatmospheric intra-articular pressures (the physiological range), only recording the supra-atmospheric arm of the curve. The sigmoid shape warrants explanation.

The sigmoid shape is caused by the changes in elastance. In the dog knee there was a large rise in pressure per unit volume (high elastance) at subatmospheric pressures. Elastance was low at atmospheric pressures, and thereafter increased as a linear function of pressure. Knight & Levick (1982*a*) observed a similar response in rabbits' knees, although elastance appeared to be more sensitive to sub- and supra-atmospheric pressures (regression slopes of mean elastance on pressure were $-12{\cdot}6$ and $1{\cdot}08$ ml^{-1} respectively) than that found in the dogs' knee in this study ($-1{\cdot}21$ and $0{\cdot}26$ ml^{-1}). The size of the difference is probably related to the large difference in size of the joints. The synovial surface area in rabbits weighing approximately 3·5 kg was estimated to be 16 cm^2 (Levick, 1979). The synovial surface area in knees of dogs weighing 9, 16 and 21 kg was estimated to be approximately 28, 39 and 59 cm^2 respectively. In a large joint, increments in volume should not cause pressure to rise at the same rate as the same increments in volume in a smaller joint. Variability of joint size, the small number of dogs included in this section of the study, and a possible over-estimation of supra-atmospheric pressures using the continuous-infusion method, all probably contributed to another difference between the findings from these two studies. The change in sensitivity of elastance from sub- to supra-atmospheric pressure was not as great in the dogs' knee (approx. 5 times) as in the rabbits' knee (approx. 12 times).

The question of why the elastance of the joint changes in this way with intra-articular pressure and volume is a complex one. The elastance–pressure curve is biphasic. As it is highly unlikely that there is a major structural change in the joint capsule at the nadir of the elastance curve, it is suggested that the two components of the curve have different causes. Our results at subatmospheric pressures support the mechanical explanation given by Knight & Levick (1982*a*), that the sensitivity of elastance to subatmospheric pressures is probably due to collapse of the joint cavity. Collapse is caused by atmospheric pressure outside the knee and by the tension of the overlying muscles and ligaments around the joint. Analogous interpretations were given by Guyton *et al.* (1971) for the response of the interstitium to increased pressure and volume, and by Agostoni (1972) for the initial response of pressure to volume in the pleural cavity. Therefore, when the first small amount of fluid is introduced into the joint at subatmospheric intra-articular pressure, the increase in pressure would depend on the release of deformational forces in the joint caused by tissue tension and atmospheric pressure.

Viscosity of the intra-articular fluid, especially if the fluid is normal synovial fluid, may also be a factor contributing to high elastance at subatmospheric pressures. Attractive forces between neighbouring portions of the highly viscous synovial fluid will oppose any motion of one part of the fluid relative to another such as may be brought about by a separation of the inner capsular walls as a result of an increase in fluid volume and hydrostatic pressure. In order to explore the viscosity effects of the infusate on elastance at subatmospheric pressures more work needs to be done using infusion fluids other than non-permeable paraffin oil and highly permeable saline or Ringer of low viscosity. Even so, caution will need to be shown in extrapolating findings from non-physiological fluids to normal, or abnormal, synovial fluid.

At the higher supra-atmospheric pressures, where elastance increases, it is suggested that the fibrous structure of the capsule wall and the influence of the overlying muscles and ligaments become predominant. This phase of the pressure–volume curve can be explained by the structural integrity and changes, in the form of molecular reorientation, which determine the pressure response to a further rise in volume. Steer *et al.* (1971) have suggested that once the capsule is stretched collagen fibres become reoriented and start to bear some of the strain and it is this which may produce the observed increase in elastance at high intra-articular volumes and pressures. It should be stressed that 'joint capsule wall' is not a single discrete structure, but includes synovial interstitium (including its lymph and blood vessels), ligaments, and connective tissue envelope sealing the joint.

The effects of infusion rate and time on pressure at constant volume

Previous measurements of intra-articular pressure have shown the importance of the rate at which joint distension was produced and the duration for which it was maintained (Nade & Newbold, 1983; Knight & Levick, 1983). Intra-articular pressure measured after a given volume of fluid infusion depends on the time elapsed after the increment in volume. In this case the joint capsule structure responds to strain in a visco-elastic manner (Myers & Palmer, 1972; Levick, 1979). Ropes & Bauer (1953) found intra-articular pressure to vary markedly in damaged joints with effusions, and it did not appear to be related to aetiology, volume, or duration of the effusion. However, in contrast to their clinical observations, for a given joint size and joint angle, in experimental studies there was a good correlation between the change in intra-articular pressure for a given change in fluid volume both in this study, and by other investigators (Palmer & Myers, 1968; Knight & Levick, 1982*a*).

The effects of joint angle on intra-articular pressure at various fluid volumes

Some of the pressure–volume experiments in the present study were carried out with the knee joint angle at approximately 125 deg, the angle at which intra-articular pressure is usually lowest. However, compliance of the joint and both size and angle of the joint throughout its physiological range affect intra-articular pressure, often causing supra-atmospheric pressures. Apart from recent studies by Knight & Levick (1982*a*) and O'Driscoll *et al.* (1983) who investigated the effects of joint angle on the pressure–volume relationship in the knee joints of rabbits, little work has been concentrated in this area. In the present study intra-articular pressures in the dog's knee were found to be subatmospheric at over 60% of the possible joint positions throughout the entire normal range of flexion–extension. Although this does not mean that joints are maintained at subatmospheric pressures for most of the time, the angles at which pressure is normally subatmospheric were observed to be those in which resting dogs commonly adopt.

With normal intra-articular fluid volume, supra-atmospheric pressures developed only at joint positions more flexed than 80 deg, and across a very small range when the joint was fully extended. In this study it is shown that a small amount of fluid infused into a joint at subatmospheric pressure caused a large rise in pressure. The pressure–volume curves measured when the joint was in a position of 110, 120 and 125 deg (when the starting pressure was subatmospheric) were not as steep as those measured when the joint was more flexed at 80 or 50 deg and the starting pressure was supra-atmospheric. This is understandable if the response is related to the elastance of the joint (Fig. 10). As pressures became higher elastance increased quite rapidly. Progressive flexion of the knee joint, as demonstrated by the casts in Fig. 12, caused the anterior portion of the capsule to be stretched and flattened over the femur. As the suprapatellar pouch contributed two-thirds of the total synovial surface area, the size of the joint space must be severely reduced when the joint is in the flexed state. When such a flexed joint is infused the elastance of the tissues increases more rapidly at lower infusion volumes than it would in a joint at an angle of 125 deg, when the joint space is at a maximum.

Volume expansion restricted the range of joint movement. In preliminary experiments, when a joint was suddenly moved into flexion shortly after a fluid infusion to a high pressure, rupture of the joint capsule often occurred. This suggests that some time is required for structural rearrangement of the capsular tissues to occur in response to stress created by stretching the capsule. Rupture of the fluid-filled capsule following sudden flexion is probably the result of an inability of the tissues to adapt to the sudden increased tension within such a short period of time. Jayson & Dixon (1970*b*) also found that large volume simulated effusions in human knees limited the range of movement that could be attained by the subjects, and in some cases produced capsular rupture.

The effects of dog weight on the pressure–volume curve

In dogs, although there is variation in joint size, even between animals of similar size and breed, a correlation between weight of the animal and elastance was found. This was the case only when the over-all weight of the dogs was taken into account (Fig. 11). There was considerable variation in joint size among animals used in this study, and animals used in other studies whose size is more readily controlled by specific breeding. However, the variation in joint size only affected the absolute pressure and volume levels. It is pertinent to indicate that the *patterns* and *direction* of change in these parameters among different species, including humans, rabbits and dogs, are similar.

Compartments of the joint cavity

The shape of the joint space is determined partly by the femur, tibia and patella, and partly by the surrounding 'capsular' structure, muscles and fasciae. The casts of the joint space (Fig. 12*A*–*D*) showed that parts of the joint cavity form small pouches and narrow channels between the ligamentous attachments and around the menisci. Similar channels have also been demonstrated in casts of the rabbit knee (Knight & Levick, 1982*b*). They form a communication between the anterior portions of the joint, and that part of the joint which lies posterior to the condyles of the femur. From the two joint positions shown in Fig. 12 it did not appear that this communication was closed off during flexion of the volume-expanded joint. In fact the fluid was pushed out of the suprapatellar region and into the infrapatellar and posterior portions of the joint. This has also been observed from radiographs during flexion of the human knee (Menschik, 1976, as reported by Levick, 1983).

Knight & Levick (1982*b*) found in rabbits' knees that at low suprapatellar pressures no hydraulic communication occurred between the anterior and posterior portions of the joint. They demonstrated two anatomically continuous, but hydraulically separate, compartments at low volumes (anterior and posterior) when they infused the joint at only one infusion site, the suprapatellar region. In the present study intra-articular communication at very low physiological pressures was not investigated.

In normal daily usage the extent of knee joint positions frequently encompassed is less than the possible range of movement of the joint, and is varied among different species. During normal standing and walking for man and the knee joint positions range from full extension 180 deg (standing) to 160 deg (during walking). In dog, and in rabbit during slow hopping, they range from 125 to 80 deg, and 75 to 40 deg respectively. These values were measured on awake animals moving freely about the laboratory. It is interesting to note that most physiological studies of rabbit synovial fluid dynamics have been with the knee held in positions more extended than 75 deg. The results of studies carried out with joints in positions less commonly used than those for normal standing and walking ('fleaing' or 'scratching' in the rabbit for example) should be viewed cautiously when data from studies using different experimental animals are compared.

The significance of pressure changes and elastance in the knee joint

At over half of the positions throughout the full range of movement of the dog's knee intra-articular hydrostatic pressures are subatmospheric (Nade & Newbold, 1983). These joint positions are from almost full extension to approximately 80 deg flexion. During normal movement, such as walking and running, the knee is rarely flexed beyond 90 deg and for a good part of the time during this type of movement the joint is loaded, i.e. it is supporting almost the full weight of the body in bipedal humans, and some lesser part of the body weight in quadrupedal dogs. This means that intra-articular hydrostatic pressures are usually subatmospheric during normal daily activity. As previously reported, intra-articular hydrostatic pressures have been shown to become substantially more negative in both human knees (Jayson & Dixon, 1970*c*) and dogs' knees (Nade & Newbold, 1983) when the joint is in the more extended positions and loaded. What functional roles do these negative pressures play? It may be that the maintenance of subatmospheric pressures in synovial joints not only allows for fluid ingress, but adds substantially to the stability of a joint. It has been reported that distraction of a joint requires considerable force when it is in a position at which the intra-articular pressure is subatmospheric, whereas at supra-atmospheric pressures it requires very little force (Semlak & Ferguson, 1970).

The strength of the soft tissue structures, i.e. the capsule, ligaments, fascia and skin can be expressed in terms of their resistance to deformation when stressed, i.e. their elastance. Elastance is a variable markedly influenced by the intra-articular pressure. In flexed normal joints, when intra-articular pressure is supra-atmospheric, stability is probably adequate due to the increase in elastance. Despite the fact that elastance increases with increasing intra-articular pressure and volume, visco-elastic response (stretch) of the capsular tissues has an opposing effect with time (Knight & Levick, 1983). The duration of an effusion and its change in volume influences the stability of the joint. Stability must be severely reduced in joints with long-standing high-volume effusions in which chronic stretch of the tissues has occurred.

We are grateful for financial support for this study from the Research Committee of the Faculty of Medicine in the University of Western Australia, the Board of Directors of Sir Charles Gairdner Hospital, the Australian Orthopaedic Association Research Fund, and the Department of Surgery in the University of Western Australia. Expert technical assistance was given by Mr Peter Burrows.

REFERENCES

AGOSTONI, E. (1972). Mechanics of the pleural space. *Physiological Reviews* **52**, 57–128.

CAUGHEY, D. E. & BYWATERS, E. G. L. (1963). Joint fluid pressure in chronic knee effusions. *Annals of Rheumatic Diseases* **22**, 106–109.

EYRING, E. J. & MURRAY, W. R. (1964). The effect of joint position on the pressure of intra-articular effusion. *Journal of Bone Joint Surgery* **46**, 1235–1241.

GUYTON, A. C. (1963). A concept of negative interstitial pressure based on pressures in implanted perforated capsules. *Circulation Research* **12**, 399–414.

GUYTON, A. C., GRANGER, H. J. & TAYLOR, A. E. (1971). Interstitial fluid pressure. *Physiological Reviews* **51**, 428–558.

Jayson, M. I. V. & Dixon, A. St. J. (1970*a*). Intra-articular pressure in rheumatoid arthritis of the knee. I. Pressure changes during passive joint distension. *Annals of Rheumatic Diseases* **29**, 261–265.

Jayson, M. I. V. & Dixon, A. St. J. (1970*b*). Intra-articular pressure in rheumatoid arthritis of the knee. II. Effect of intra-articular pressure on blood circulation to the synovium. *Annals of Rheumatic Diseases* **29**, 266–268.

Jayson, M. I. V. & Dixon, A. St. J. (1970*c*). Intra-articular pressure in rheumatoid arthritis of the knee. III. Pressure changes during joint use. *Annals of Rheumatic Diseases* **29**, 401–408.

Knight, A. D. & Levick, J. R. (1981). Pressure–volume relationships and fluid compartmentation in synovial joints. *Journal of Physiology* **319**, 36–37*P*.

Knight, A. D. & Levick, J. R. (1982*a*). Pressure–volume relationships above and below atmospheric pressure in the synovial cavity of the rabbit knee. *Journal of Physiology* **328**, 403–420.

Knight, A. D. & Levick, J. R. (1982*b*). Physiological compartmentation of fluid within the synovial cavity of the rabbit knee. *Journal of Physiology* **331**, 1–15.

Knight, A. D. & Levick, J. R. (1983). Time-dependence of the pressure–volume relationship in the synovial cavity of the rabbit knee. *Journal of Physiology* **335**, 139–152.

Levick, J. R. (1979). The influence of hydrostatic pressure on trans-synovial fluid movement and on capsular expansion in the rabbit knee. *Journal of Physiology* **289**, 69–82.

Levick, J. R. (1983). Synovial fluid dynamics: the regulation of volume and pressure. In *Studies in Joint Disease*, vol. 2, ed. Holborow, E. J. & Maroudas, A. London: Pitman Medical.

McCarty, D. J., Phelps, P. & Pyenson, J. (1966). Crystal-induced inflammation in canine joints. *Journal of Experimental Medicine* **124**, 99–114.

Mills, J., Newbold, P. J. & Nade, S. (1982). Small animal joint servo-manipulator. *Australasian Physical and Engineering Sciences in Medicine* **5**, 166–170.

Myers, D. B. & Palmer, D. G. (1972). Capsular compliance and pressure-volume relationships in normal and arthritic knees. *Journal of Bone and Joint Surgery* **54-B**, 710–716.

Nade, S. M. & Newbold, P. J. (1983). Factors determining the level and changes in intra-articular pressure in the knee joint of the dog. *Journal of Physiology* **338**, 21–36.

Newbold, P. J. (1983). Some aspects of the physiology of the canine knee joint. Ph.D. Thesis, University of Western Australia.

O'Driscoll, S. W., Kumar, A. & Salter, R. B. (1983). The effect of the volume of effusion, joint position and continuous passive motion on intra-articular pressure in the rabbit knee. *Journal of Rheumatology* **10**, 360–363.

Palmer, D. G. & Myers, D. B. (1968). Some observations of joint effusions. *Arthritis and Rheumatism* **11**, 745–755.

Ropes, M. W. & Bauer, W. (1953). *Synovial Fluid Changes in Joint Disease*. Cambridge, MA: Harvard University Press.

Semlak, K. & Ferguson Jr, A. B. (1970). Joint stability maintained by atmospheric pressure. *Clinical Orthopedics* **68**, 294–300.

Steer, G., Jayson, M. I. V., Dixon, A. St. J. & Beighton, P. (1971). Joint capsule collagen. Analysis by the study of intra-articular pressure during joint distension. *Annals of Rheumatic Diseases* **30**, 481–486.