Original Paper

Eur Surg Res 1995;27:197–204

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Changes in Intraosseous Pressure at the Distal Femoral Epiphysis Induced by Variations in Knee-Joint Position and Intracapsular Saline Infusion

An Experimental Study in Dogs

Key Words
Bone hemodynamics
Intraosseous pressure
Epiphysis

Abstract
Hemodynamic changes at the distal femoral epiphysis measured by recording intraosseous pressure (IOP) were investigated in mature and juvenile dogs after changes in knee-joint position and intracapsular infusion of 3 ml isotonic saline solution. Juvenile and mature animals responded to infusion test with a similar 5-fold increase in intracapsular pressure. A 2-fold increase in IOP was found when knee-joint flexion passed from 30° to complete flexion. In juvenile dogs, IOP values were lower than in adults both in complete knee flexion and during infusion test. The similar response to joint hyperpressure tests observed in adult and juvenile dogs suggests that the barrier effect of the growth plate for epiphyseal venous drainage has no major influence in the hemodynamics of the distal femoral epiphysis.

Introduction

It has been well documented that simulated hip-joint effusion (intracapsular hyperpressure (ICP) test) in experimental animals leads to increased intraosseous pressure (IOP) and decreased regional blood flow at the femoral head [1–3]. In fact, a simple mechanism of intracapsular hip venous tamponade produced avascular necrosis of the femoral head in puppies [4–6]. Such a mechanism impairing epiphyseal blood flow has been clinically demonstrated in transient synovitis of the hip [7] as well as in juvenile chronic arthritis of the hip [8]. Furthermore, changes in ICP have been interpreted as the underlying cause of

Received:
December 7, 1993
Accepted:
June 27, 1994

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0014–312X/95/
0273–0197$8.00/0

Table 1. Characteristics of animals included in the experiment

Animal	No.	Sex	Age months	Weight kg	Basal ICP mm Hg	Basal IOP mm Hg
Juvenile	1	M	7	18	16	16
	2	M	5	6	10	13
	3	M	6	16	16	50
	4	F	5	6	23	13
Adults	5	M	24	24	23	13
	6	M	36	25	10	46
	7	F	60	24	6	70
	8	M	60	18	20	100
	9	M	48	22	10	20
	10	F	72	17	6	83

the impaired blood flow within the femoral head epiphysis in Perthes' disease [4, 9].

It has also been demonstrated in experimental and in human clinic studies that certain joint positions induce intracapsular hyperpressure and subsequent impairment of subchondral bone perfusion [10–13]. A clinical example of the crucial influence of joint position on the epiphyseal blood flow is the frequent development of avascular necrosis of the hip in children with congenital dislocation of the hip treated by immobilization in flexion-abduction with maximun rotation of the hip. That position produces a hazardous increase in the ICP [14, 15], and it is the probable cause of the avascular necrosis that also occurs in the nonsymptomatic contralateral hip immobilized in the same position.

Although much research has been carried out, the influence of the epiphyseal growth plate on the hemodynamics of juxta-articular bone during joint intracapsular hyperpressure is still controversial since few authors have compared juvenile and adult animals [1, 4, 5, 16]. This study was aimed at investigating this issue in greater detail. More specifically, we have analyzed the influence of changes in knee-joint position and intracapsular saline infusion on the blood flow at the distal femoral epiphysis. Variations in IOP were recorded as a measure of the blood flow within the femoral epiphysis. Adult and juvenile animals were compared in order to analyze if the presence of the distal femoral growth plate would be a barrier for venous drainage, increasing then the effects of knee-joint tamponade.

Material and Methods

Ten mongrel dogs with an average age of 32 months (range 5–60) and a mean body weight of 17 kg (range 6–25) were used in the experiment. Six animals with complete skeletal maturity as shown by the absence of physeal growth plate were considered as adults. There were 4 skeletally immature animals exhibiting active physeal growth plate at the distal femur and therefore were considered as 'juvenile' (table 1).

Animals underwent general anesthesia with natriumthiopenthal (25 mg/kg). When muscle fibrillation or contractions were observed as a sign of pain, natriumthiopenthal was reinjected in lower dosage (5 mg/kg). Reinjection was repeated if pain signs were newly apparent. The experiments do not surpass 30 min of continuous assisted ventilation. Halothane was not used for anesthesia trying to avoid the progressive halothane-induced vasodilatation and subsequent increment in limb blood flow which has been described in similar experiments [11].

Intraosseous, intracapsular and systemic blood pressures were continuously recorded using a three-channel fluid-filled electromanometer HP 78342A

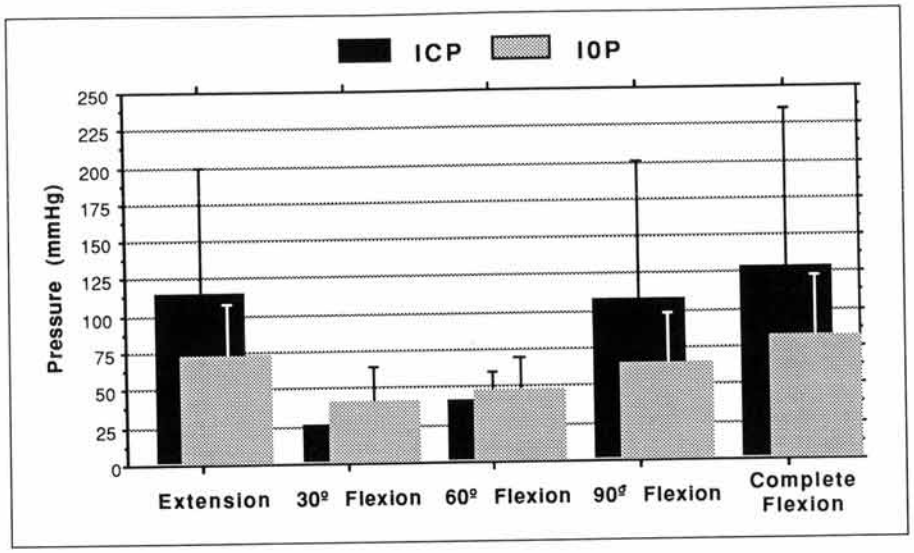

Fig. 1. Variations in ICP and IOP in different knee-joint positions (mean ± SD).

(Hewlett Packard, Waltham, Mass., USA). IOP was measured in the distal femoral epiphysis by transcutaneous bone cannulation according to Bünger et al. [10, 17]. The insertion of the cannula into the epiphysis, distal to the growth plate, was performed under the guidance of an image intensifier. The tip of the cannula was placed in the middle of the lateral femoral condyle. The knee-joint level was chosen as reference zero pressure level for both IOP and ICP. The basal IOP was considered that obtained after an equilibration period of 5 min postcannulation.

ICP was assessed by insertion of a 18-gauge flexible needle within the expansion of the knee-joint capsule below the quadriceps (suprapatellar compartment). Polyethylene catheters were inserted into the femoral artery near to the ipsilateral knee joint for continuous systemic blood pressure recording.

Data concerning basal IOP and ICP values, and blood pressures are summarized in table 1. Variations in both IOP and ICP were obtained either by injection of 3 ml isotonic saline solution into the knee joint or by gradual changes in knee-joint position. These changes were knee extension, 30°, 60°, 90° flexion, and complete knee flexion.

Mean and SD values were calculated from all parameters. Statistical analysis was first performed by assessment of the normal distribution of data using the analysis of variance (ANOVA). For comparison between groups, the Student's t test for paired data and simple regression curves were applied. Differences were considered significant when p value was <0.05.

Results

Systemic blood pressure remained constant during the experiment, the average being 184 mm Hg (166–206) for systolic and 134 mm Hg (116–153) for diastolic pressure. In basal conditions –30° knee flexion – IOPs were superior to ICP in all cases (average 38 and 14 mm Hg respectively).

Figure 1 shows results of ICP and IOP recorded in the different knee positions investigated in the whole series of animals. When increasing stepwise the flexion angle of the knee from 30° to complete flexion, a statistically significant gradual increase was found in both ICP and IOP. A 5-fold increment in ICP was found from 30° flexion to complete flexion (26 ± 12 vs. 129 ± 107 mm Hg, $p < 0.001$) while IOP values disclosed a 2-fold

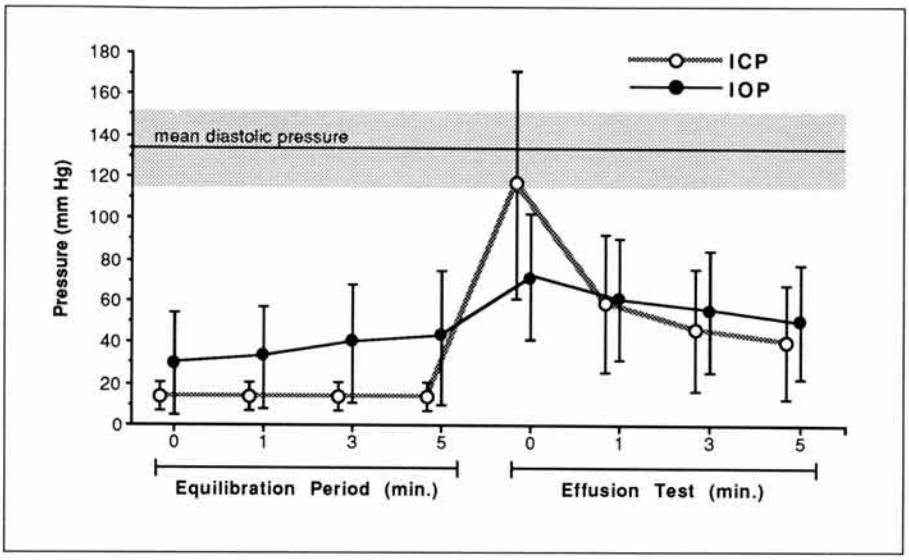

Fig. 2. Variations in ICP and IOP during saline joint infusion (mean ± SD).

Table 2. ICP and IOP in adult and juvenile animals in different knee-joint positions and after saline infusion test (mean and SD values in mm Hg)

	ICP				IOP			
	adult		juvenile		adult		juvenile	
	mean	SD	mean	SD	mean	SD	mean	SD
Extension	128	86	96	92	87	31	47	23
30° flexion	29	13	21	11	50	24	27	13
90° flexion	130	11	74	43	85	24	33	13*
Complete flexion	155	127	90	64	111	25	37	14**
Infusion test	133	51	93	59	90	22	44	15*

* $p < 0.01$; ** $p < 0.001$.

increase (41 ± 23 vs. 81 ± 43 mm Hg, $p < 0.01$). The IOP increase between 30 and 60° flexion was the only one being not statistically significant. In complete flexion, values reached those found in complete extension and therefore differences between these two extreme joint positions were not statistically significant (fig. 1).

IOP never surpassed the diastolic blood pressure in any case. However, ICP was higher than both systolic and diastolic pressure in 3 out of 10 animals (1 juvenile and 2 adults). There was no correlation between ICP and IOP values in any of the joint positions investigated. There was no correlation of ICP to either systolic or diastolic blood pressure. ICP

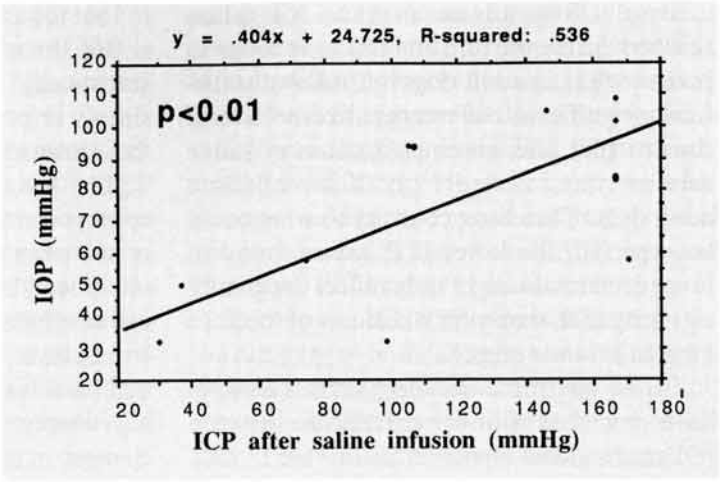

Fig. 3. Correlation between ICP and IOP after saline infusion test in the whole series.

induced by synovial fluid had no dependence of blood pressure.

After infusion of 3 ml isotonic saline solution into the knee joint in 30° flexion, both ICP and IOP increased significantly (ICP average increase 103 mm Hg, $p < 0.0005$; IOP 42 mm Hg, $p < 0.001$) (fig. 2). First, an elevation of ICP occurred followed immediately by a less marked increase in IOP. ICP reached values higher than the diastolic pressure in 6 animals but never higher than the systolic blood pressure. Increments in ICP correlated with IOP rising immediately after saline infusion (linear coefficient of $r = 0.732$, $p < 0.01$; fig. 3). IOP was always inferior to the diastolic pressure. Five minutes after saline infusion, ICP and IOP recovered basal values.

Some differences were detected when juvenile dogs were compared to adults in the two experiments (table 1). In both adult and juvenile animals, ICP and IOP responded with a marked increase either to joint effusion or complete flexion. Analyzing differences within groups of juvenile and adult dogs, variations in IOP during gradual flexion were statistically significant in adult but not in juvenile animals. Differences in IOP between adult and juvenile animals were only statistically significant at both 90° and complete knee flexion (table 2). In juvenile animals, IOP did not increase as much as in adults. Differences were statistically significant for both the effusion test ($p < 0.01$) and complete flexion of the knee joint ($p < 0.001$). Regarding ICP, there were no differences between groups, and within the group of juvenile animals.

Discussion

Blood flow at the distal femoral epiphysis assessed indirectly by IOP recording was investigated after changes in knee-joint position and intracapsular saline infusion in a series of dogs. Adult and juvenile animals were compared in order to evaluate the influence of the distal femoral growth plate as barrier for venous drainage. In our experiment, all animals responded to saline infusion within the knee joint and changes in knee-joint position with a similar 5-fold increase in ICP and a subsequent 2-fold increase in IOP.

Basal ICP records and maximal ICP values reached during the infusion test were lower in juvenile than in adult dogs but without statistically significant differences. Irrespective of the articular size, an equal amount of saline solution was injected in both juvenile and adult dogs. Therefore, contrary to what could be expected, the lower ICP values found in juvenile animals might only reflect the greater elasticity of the capsular structures of the knee joint in juvenile dogs.

In the last three decades, several authors have described a direct correlation between IOP and regional blood perfusion [10, 17–20]. In 1975, Wilkes and Visscher [21] demonstrated that IOP recording is a reliable method for bone blood flow assessment. IOP is a measurement of the gradient between arterial and venous pressure and therefore reflects bone blood flow. Direct flow measures cannot be made in this way but changes in flow are reflected by changes in IOP. In fact, human studies demonstrated that changes in IOP reflect changes in bone blood flow in patients with femoral neck fractures [22].

In our investigation, ICP and IOP reached values near the diastolic blood pressure by the influence of changes in knee-joint position. We found a 2-fold increase in IOP when knee-joint flexion passed from 30° to complete flexion. Our findings were in accordance with those reported by Arnoldi [13] in which progressive flexion of the fetlock joint in horses induced a significant rise in IOP measured at the metacarpal bone, approaching but never exceeding systemic blood pressure.

In this study, some discrepancies in the response of IOP to both infusion test and after changes in knee-joint positions were found between mature and juvenile animals. Although there were no statistically significant differences between groups, lower IOP values were registered in immature dogs, both in basal conditions and during joint stress. Contrary to that found in adult dogs, variations in IOP within the group of juvenile animals were not statistically significant. This feature could simply respond to the lower ICP recorded in these animals.

The hemodynamics of the distal femoral epiphysis and knee-joint ICP have been closely related in previous studies in the sense that increments in ICP result in impairment of the intramedullary vascular supply [3, 10, 12, 23]. It has been demonstrated in immature animals that IOP increases up to 2- to 3-fold during venous tamponade of the knee joint, changes in articular position having an effect on bone circulation [10, 24]. Hansen et al. [3] investigated the impact of joint effusion on intraosseous blood flow, measured by ^{99m}Tc-diphosphonate scintimetry. A joint tamponade equivalent to 75 mm Hg reduced the uptake in the distal femoral epiphysis in growing dogs by 20%. In another experiment, blood flow assessed by radioactive microspheres at the same level was unchanged when ICP reached 50% of the mean arterial pressure [23]. Our findings are in accordance with those described previously, in the sense that a 2-fold increase in IOP reflects a tamponade effect decreasing blood flow. However, all these reports deal only with immature dogs.

In normal conditions, IOP in the canine distal femoral epiphysis varies widely from puppies to adult dogs (from 40–60 to 18–20 cm of water, respectively) [25, 26]. No such differences occurred at the femoral head where IOP has been reported very similar in both adult and juvenile dogs [1]. However, in our experiment, IOP was found to be higher in mature animals than in juvenile dogs (50 ± 24 vs. 27 ± 13 mm Hg). As in other studies, there was a wide variation in basal IOP determinations within our sample. In the literature, the same variability of results has been reported in both proximal and distal epiphysis either for IOP or for intraosseous blood

flow assessed by different methods [1, 16, 27]. It has been suggested that this large variability of results reflects real differences between animals [1, 26].

In the hip joint, it is well documented either by clinical or experimental studies that hip-joint effusion induces a tamponade effect due to occlusion of retinacular vessels, diminishing blood flow into the femoral head [1, 3–5, 12, 13, 16]. Several issues such as the arterial or venous nature of the occlusion, the minimal ICP threshold to produce bone blood flow stoppage, and the role of the epiphyseal growth plate barrier limiting venous drainage during the growth stage are still controversial.

Assessing bone viability with tetracycline labeling after venous occlusion in juvenile dogs, Woodhouse [5] found that continuous ICP higher than 50 mm Hg over 12 h induced bone necrosis of the femoral head. In similar experiments on puppies, Tachdjan and Grana [4] reported that the development of avascular necrosis required an ICP of 200 mm Hg for at least 10 h. More recently, Borgsmiller et al. [6], using a hydrogen washout technique, confirmed that blood flow in the proximal femoral epiphysis is eliminated with an ICP over 150 mm Hg. At 50 mm Hg ICP, the regional femoral head blood flow was unchanged. All these experimental findings applied for the proximal femoral epiphysis of juvenile dogs, but cannot be imported to distal epiphysis, since the knee joint has a different pattern of subsynovial circulation.

After infusion of the hip joint with saline solution, Launder et al. [1] found a different behavior of mature and immature dogs regarding pressure-flow relationships in the femoral head. In immature animals, venous tamponade due to an ICP reaching 65 cm of water resulted in 2.5-fold increased IOP and 60% decreased blood flow measured by isotopically labelled microspheres. These findings could not be confirmed in adult dogs. The absence of epiphyseal growth plate permitting intramedullary venous drainage in the mature animal was thought to be the reason for such differences. In fact, Fitzgerald [28] demonstrated in adult dogs the presence of free anastomosis between epiphyseal and metaphyseal vessels, similar to that found by Trueta and Harrison [29] in adult human specimens.

In contrast, it has also been suggested that the hip joint of both juvenile and adult dogs is similarly exposed to venous tamponade and subsequent decrease in intraosseous blood flow. This feature has been demonstrated by Vegter and Klopper [16] using laser Doppler flowmetry. In their study, ICP over 100 cm of water diminished the femoral blood flow by more than 50%, but no differences were detected between adults and puppies.

Our results concerning blood flow variations at the distal femoral epiphysis induced by two different intra-articular hyperpressure tests in adult and juvenile dogs are similar to those found by Vegter and Klopper [16] at the proximal femoral epiphysis. The equal response to knee-joint venous tamponade observed in adult and juvenile dogs seems to diminish the importance of the growth plate as a barrier for venous drainage of the distal femoral epiphysis. Our findings also support the hypothesis that the impairment of vascular supply at the distal femoral epiphysis described by several authors [9–13] in immature dogs after knee-joint tamponade can be extrapolated to mature animals, as it has been shown in this study. It seems that, at least in the distal femoral epiphysis, the growth plate is not an obstacle for venous blood flow.

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