MICROANGIOGRAPHIC, HISTOLOGICAL AND RADIOGRAPHIC
STUDY OF THE FEMORAL HEAD FOLLOWING
EXPERIMENTAL HIP DISLOCATION
IN RABBITS

BY

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We accept this thesis as conforming to the required standard.

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ABSTRACT

In 220 rabbits (65 mature and 155 immature) the effects of dislocation, persistent dislocation and reduction at varying intervals (immediately, 12, 24 and 48 hours after dislocation) of the left hip were studied by microangiographic, histological and radiographic examination.

Dislocation of the left hip was induced manually under anaesthesia by a dorsally applied force with the hip held adducted and internally rotated. Reduction was effected by ventral traction with the hip in the same position. The right hip was untouched and used as a control in all cases.

In 135 animals, a tracer dye was infused into the abdominal aorta proximal to its bifurcation under standard conditions of temperature and pressure. This infusion was done at 10 minutes, and at 1, 3, 5, and 7 days after dislocation or reduction. The femoral heads were then processed and studied under stereomicroscopy. Histological and radiographic studies were made in the remaining 85 animals at intervals between 3 and 10 weeks after dislocation or reduction.

In immature animals, severe dye perfusion deficit was observed in all cases within 10 minutes of dislocation. This was maximal in the antero-medial half of the femoral head. The deficit was increased at 24 hours and persisted until 5 days after dislocation. At the seventh day recovery had commenced. A profound perfusion deficit was also noted within 10 minutes of immediate reduction, however, recovery was observed at 24 hours and was almost complete at 5 - 7 days. The rate of recovery in those animals in which the dislocation was reduced at 12, 24 and 48 hours did not differ from that observed in unreduced animals. In adult animals, significant circulatory disturbance was infrequently observed after
dislocation and persistent dislocation. Consequently, the beneficial effects of reduction, if any, were obscured. The epiphysio-metaphysial vascular anastomoses across the epiphyseal scar were filled with dye in all mature rabbits and seemed to act as a route of blood supply and drainage in adult animals.

Extensive histological avascular necrosis of the femoral head was observed in the majority of animals, but was significantly more common in immature rabbits. Less extensive and less common avascular necrosis was observed in immature animals after immediate reduction. However, reduction delayed to 12 hours or later was not associated with a lower incidence of bone death.

Abnormal radiological findings were common and varied. Specific alteration in density and outline of the femoral head was however infrequently observed, but correlated well with the histological findings. Decreased radiodensity was associated with inbalanced bone resorption and hyperaemia, and increased radiodensity with bone death and new bone apposition.

It is concluded that traumatic dislocation causes embarrassment and sequential changes in the circulation within the femoral head in rabbits. The perfusion deficit is more severe in immature animals as the intra-osseous epiphysio-metaphysial vessels minimize this circulatory disturbance in adult animals. Early reduction enhances early and complete recovery of blood supply in immature animals. Varying degrees of avascular necrosis of the femoral head occur in both adult and immature animals with and without reduction, but is more common and extensive in immature animals. Abnormal radiological features within the femoral head are infrequently observed up to ten weeks after dislocation but correlate well with the histological findings when present.
### INDEX OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. INTRODUCTION AND PURPOSE OF THE STUDY</td>
<td>1</td>
</tr>
<tr>
<td>II. REVIEW OF THE LITERATURE</td>
<td>3</td>
</tr>
<tr>
<td>III. BONE CIRCULATION</td>
<td>3</td>
</tr>
<tr>
<td>---</td>
<td></td>
</tr>
<tr>
<td>Anatomy -- General</td>
<td>4</td>
</tr>
<tr>
<td>-- The femoral Head in Man</td>
<td>13</td>
</tr>
<tr>
<td>-- Comparative Anatomy</td>
<td>22</td>
</tr>
<tr>
<td>-- Functional Importance in Man and Animals</td>
<td>32</td>
</tr>
<tr>
<td>Physiology-General</td>
<td>37</td>
</tr>
<tr>
<td>-- The Femoral Head</td>
<td>41</td>
</tr>
<tr>
<td>TRAUMATIC DISLOACTION OF THE HIP</td>
<td>43</td>
</tr>
<tr>
<td>---</td>
<td></td>
</tr>
<tr>
<td>Clinical - In Man - Classification</td>
<td>44</td>
</tr>
<tr>
<td>Adults</td>
<td>45</td>
</tr>
<tr>
<td>Children</td>
<td>47</td>
</tr>
<tr>
<td>Avascular Necrosis</td>
<td>49</td>
</tr>
<tr>
<td>---</td>
<td></td>
</tr>
<tr>
<td>Experimental - In Animals</td>
<td>54</td>
</tr>
<tr>
<td>III. MATERIALS AND METHODS</td>
<td>57</td>
</tr>
<tr>
<td>The Experimental Model</td>
<td>57</td>
</tr>
<tr>
<td>Investigation - A. Microangiography</td>
<td>58</td>
</tr>
<tr>
<td>B. Histology</td>
<td>66</td>
</tr>
<tr>
<td>C. Radiography</td>
<td>68</td>
</tr>
</tbody>
</table>
IV. RESULTS

A. Microangiography

Normal Uninjured Rabbits

Dislocation and reduction, Immature Animals

Dislocation and reduction, mature Animals

Reduction at 12 hours, mature and Immature animals

B. Histology

C. Radiology

General

Comparative

V. DISCUSSION

VI. SUMMARY

VII. CONCLUSIONS

VIII. BIBLIOGRAPHY
INDEX OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. (a)</td>
<td>Radiograph. Section of the Adult Human Femoral Head and Neck in the Frontal Plane.</td>
</tr>
<tr>
<td>1. (b)</td>
<td>Diagramatic Illustration of the Metaphyseal and Epiphyseal Constituents of the Femoral Head.</td>
</tr>
<tr>
<td>2.</td>
<td>Microarteriogram of the Proximal Human Adult Femur.</td>
</tr>
<tr>
<td>3. (a)</td>
<td>Microarteriogram of the Adult Proximal Canine Femur.</td>
</tr>
<tr>
<td>3. (b)</td>
<td>Microangiogram of the Immature Canine Head and Neck of Femur.</td>
</tr>
<tr>
<td>4.</td>
<td>Microarteriogram of the Proximal Rabbit Femur.</td>
</tr>
<tr>
<td>5.</td>
<td>High Magnification Microarteriogram of the Proximal Rabbit Femur.</td>
</tr>
<tr>
<td>6.</td>
<td>Microarteriograms of the Rabbit Femur.</td>
</tr>
<tr>
<td>7.</td>
<td>High Magnification Chinese Ink Microangiogram of the Juxta-articular Vascular system of the Femoral Head in the Rabbit.</td>
</tr>
<tr>
<td>8. (a)</td>
<td>Microangiogram of the Immature Rabbit Femoral Head.</td>
</tr>
<tr>
<td>8. (b)</td>
<td>Microangiogram of the Adult Rabbit Femoral Head.</td>
</tr>
</tbody>
</table>
9. The General Set Up of the Infusion .............. 60
10. The Bladder Before and After Satisfactory Perfusion with Dye .............. 61
11. The Posterior Aspect of the Proximal Femora After Dislocation of the Left Hip and Infusion ......................... 62
12. The Final Preparation Before Stereomicroscopic Analysis ......................... 62
13. High Magnification of the Final Preparations before Stereomicroscopic Analysis ......................... 63
15. Antero-posterior x-ray of the Pelvis and Hips within 48 hours of Unreduced dislocation of the Left Hip ......................... 67
16. Qualitative analysis of Dye Perfusion of the Femoral Head ......................... 69
17. Qualitative analysis of Dye Perfusion of the Femoral Head ......................... 69
18. Qualitative analysis of Dye Perfusion of the Femoral Head ......................... 70
19. Semiquantitative analysis of Dye Perfusion of the Femoral Head ......................... 70
20. The Results of Unreduced Dislocation in Immature Rabbits at 10 minutes and 24 hours after Dislocation ......................... 73
21. The Microangiographic Pattern 7 Days following Unreduced Dislocation in Immature Rabbits.......................... 74

22. The Microangiographic Pattern in Immature Animals at 10 minutes after Immediate reduction and 10 minutes after Unreduced dislocation.......................... 76

23. The Microangiographic Pattern in Immature Animals at 24 hours after Immediate Reduction and 7 days after Unreduced dislocation.......................... 77

24. The Microangiographic Pattern in Immature Animals at 5 days and 7 days following Immediate Reduction.......................... 78

25. The Microangiographic Pattern in Mature Rabbits at 10 minutes and 7 days after Unreduced Dislocation.......................... 80

26. Histological Section (H. & E.) of the Normal Femoral Head.......................... 83

27. Histological Section of the Left Femoral Head following Prolonged Unreduced Dislocation.......................... 83

28. Histological Section of the Left Femoral Head following Dislocation.......................... 85

29. High Power Photomicrograph from Dislocated Left Femoral Head.......................... 85
30. Analysis of the Histological Findings ........................................ 86

31. In Vitro Radiograph of the Right and Left Proximal Femora from an Adult Rabbit Eight Weeks following dislocation, and Reduction at 24 hours ........................................... 90

32. In Vitro Radiograph of the Proximal Femora from an Adult Rabbit with long-term Unreduced Dislocation of the Left Hip ............. 91

33. Histological Sections of the Femoral Head following Infusion ........................................... 95
TABLES

<table>
<thead>
<tr>
<th>Table Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Clínico Radiological outcome in 207 Hips following Traumatic Posterior Dislocation</td>
<td>116</td>
</tr>
<tr>
<td>II. Outline of Experiment I</td>
<td>117</td>
</tr>
<tr>
<td>III. Outline of Experiment II</td>
<td>118</td>
</tr>
<tr>
<td>IV. Outline of Experiment III</td>
<td>119</td>
</tr>
<tr>
<td>V. Outline of Experiment IV</td>
<td>120</td>
</tr>
<tr>
<td>VI. Outline of Long-term Animals for Histological Examination</td>
<td>121</td>
</tr>
<tr>
<td>VII. Outline of Short-term Animals for Histological Examination</td>
<td>122</td>
</tr>
<tr>
<td>VIII. The Effect of Skeletal Maturity at the Time of Injury on the Histological Outcome, Regardless of Reduction</td>
<td>123</td>
</tr>
<tr>
<td>IX. The influence of Reduction on the Histological Outcome, Regardless of Skeletal Maturity</td>
<td>124</td>
</tr>
<tr>
<td>X. The Influence of Early Reduction on the Histological Outcome, regardless of Skeletal Maturity</td>
<td>125</td>
</tr>
<tr>
<td>XI. The Influence of Both Skeletal Maturity and Treatment on the Incidence of Total or Subtotal Histological Avascular Necrosis</td>
<td>126</td>
</tr>
</tbody>
</table>
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INTRODUCTION

Traumatic dislocation of the hip in man is not a rare injury and its incidence is steadily rising with the coincident increase in the complexity and speed of travel. The hip is the most stable diarthrodial joint and traumatic dislocation must therefore imply severe injury to the surrounding soft tissues. Often this is accompanied by bone and cartilage injury of the femoral head and acetabulum. The hip is furthermore the largest weight bearing joint in the body, and alteration in the congruity, composition or function of its constituents induced by dislocation may cause degenerative arthritis.

Avascular necrosis of the femoral head, a well recognized complication of traumatic dislocation, is a potent cause of osteo-arthritis. The vascular anatomy of this region suggests that damage to the blood vessels surrounding the hip is a major factor in the genesis of the ischaemic necrosis. We are however ignorant of the serial circulatory changes which may occur in the femoral head following dislocation and how they alter with time. Clinical studies repeatedly stress a number of salient contributory factors which seem to affect the outcome.

1. The severity of the injury.
2. The duration of dislocation
   and
3. The age of the patient.

These factors are however commonly inter related in the individual patient and so the separate influence of each is uncertain.
PURPOSE OF THE STUDY

1. To establish the sequential changes in blood supply of the femoral head following experimental traumatic dislocation of the hip in rabbits.
2. To evaluate the influence of the duration of dislocation.
3. To evaluate the influence of skeletal maturity.
4. To evaluate the influence of reduction.
5. To correlate these changes to the histological and radiological findings.

It is hoped this study may add important knowledge to our understanding of the problem in man.
REVIEW OF THE LITERATURE

BONE CIRCULATION

ANATOMY:

General Features

The Femoral Head in Man

Comparative Vascular Anatomy of The Femoral Head in Man and Animals

Functional Importance in Man and Animals

PHYSIOLOGY:

General Features

The Femoral Head
ANATOMY

GENERAL FEATURES:

The first suggestion that bone had a blood supply was made in 1691 by Compton Havers. He observed how large vessels pierced the shaft of long bones and ramified within in close association with the marrow fat. Albinus in 1756 published what must be the first account of the blood supply of bone studied by the injection technique. He observed blood vessels within a complex system of pores in cortical bone. These pores had been described earlier by Havers, and so are now widely known as Haversian canals.

Knowledge was slow to develop however, principally as bone, both as a tissue and as an organ, presented almost insurmountable difficulties to the investigator. Notwithstanding these difficulties the untiring interest, industry and consummate skill of the earlier anatomists and their ever increasing successors in widely diverse scientific disciplines has today presented us with an almost unlimited wealth of information and many methods of pursuing further studies of what Trueta aptly termed the "Development and Decay of the Human Frame".

The great bulk of our knowledge is based on examination of the extra-osseous and intra-osseous nature, course and behavior of blood vessels. Such investigation has been considerably enhanced by prior infusion of the vessels with materials which render their outline more obvious to the human eye or x-ray beam. Many such substances have been used,
among which Neoprene Latex, India Ink, Barium Sulphate (Micropaque), Prussian Blue have been the most rewarding. Introduction of the SPALTEHOLZ technique of bone clearance allowed the investigator to prepare translucent sections of demineralized bone allowing a remarkably accurate three dimensional analysis of the vascular anatomy, especially with the aid of stereomicroscopy. Finally light and electron microscopy has proven an important adjunct in confirming what was in most instances purely inferred by the location and behavior of blood vessels. In particular the "thick - thin" method of preparing adjacent and consecutive sections of bone has been invaluable in formulating a composite map of the morphology and functional implications of bone and its blood supply.

The classical outline of the blood supply of tubular bone was consecutively described by LANGER and LEXER. Their findings were based on gross dissection, on injection techniques and in the case of LEXER, on x-ray analysis following blood vessel infusion with a mercury-turpentine emulsion. It is now generally accepted that there are three major vascular systems in tubular bone:

1. Nutrient diaphyseal
2. Epiphyseal - metaphyseal
3. Periosteal

THE NUTRIENT DIAPHYSEAL SYSTEM:

One or more nutrient arteries enter the diaphysis of all long bones in man and animals. The number of vessels and site of entry vary with the bone and species under consideration.
LAING described an almost equal incidence of one or two nutrient vessels entering the proximal two thirds of twenty seven human femora, in the region of the linea aspera. All vessels ultimately derived from the profunda femoris artery. The nutrient artery branches immediately on reaching the marrow cavity. One superior and one inferior branch pass vertically up and down the shaft and subdivide into a variable number of medullary branches whose orientation is again principally vertical. Numerous radial branches arise from these medullary arteries and pass to the adjacent marrow and cortex. On reaching the bone ends there is at least a functional anastomosis between the diaphyseal and the epiphyseal-metaphyseal systems. The level at which these connections take place is in some dispute. BROOKS and HARRISON using micropaque of varying viscosity concluded that the nutrient and the metaphyseal systems were largely distinct and anastamosed, if at all, at the pre-capillary level. However selective interference with the nutrient vessel in rabbits was followed in time by a restoration of blood supply to the shaft from the metaphyseal system. This vouches for an effective collateral system, but time dependant.

TRUETA and CAVADIAS following investigation of nutrient vessel obliteration in rabbits' forelimb concluded that the epiphyseal-metaphyseal system in adults, and the periosteal and metaphyseal system in growing rabbits was quite capable of preventing infarction of marrow and cortex in the shaft.
SHIM and his associates confirmed TRUETAS findings. Using an indirect method of Sr clearance by bone, they found that within five minutes of nutrient diaphyseal vessel obliteration in the adult rabbit femur, still 30% of the blood supply to the shaft remained.

THE EPephySEAL - METAphySEAL SYSTEM:

A separate system of nutrient vessels enter at each end of a long bone and are responsible for nutrition of the growth plate in growing bones, the bony epiphysis, a variable amount of the metaphysis, and perhaps the basal layer of the articular cartilage. With few exceptions (the ligamentum teres) these vessels stem from the "circulus articuli vasculosus" described by WILLIAM HUNTER in 1743.

The function of the epiphyseal and metaphyseal moieties of this group of vessels differ. This is most evident in the growing bone when the growth plate separates them.

The epiphyseal vessels enter on the epiphyseal side of the growth plate (or epiphyseal scar) and characteristically traverse the bone so running at right angles to their diaphyseal counterparts. While crossing the epiphysis these vessels branch and rebranch, but continue to anastamose profusely. Small vessels are given off in radial fashion which course directly towards the articular cartilage, and growth plate, continuing to anastamose and so forming arcades of vessels (similar to those seen in the mesentery). These branches subsequently form distinct juxta articular and juxta epiphyseal vessels, end-artery in type.
The metaphyseal vessels enter on the metaphyseal side of the growth plate. They share nutrition of the metaphysis with the terminal branches of the nutrient diaphyseal vessels. The contribution made by the metaphyseal vessels alone varies with age, species and the bone in question. In adult man the proximal femoral neck is supplied in toto by perforating metaphyseal vessels, but in the newborn the principal supply is diaphyseal. TRUETA and AMATO found that the central three-fifths of the upper tibial metaphysis in rabbits was supplied by nutrient vessels. Only the outer rim was supplied by metaphyseal vessels.

Discrete fine branches from each source approach the hypertrophic and calcified layers of the growth cartilage and there play an important role in enchondral ossification.

THE PERIOSTEAL SYSTEM

A double layered system of vessels may be found in the periosteum. A rich network of arteries and veins derived from the adjacent soft tissue vasculature, ramifies in the fibrous layer. Several prominent vascular circles can be seen encircling the shaft and inter-communicating with their neighbours by vertical branches especially large at the borders of the shaft. Many small branches derive from this superficial system and form a capillary network in the deeper osteogenic layer of the periosteum known as the cambium layer. Small arteries or capillaries connect with the lattice work of vessels within the cortex, and so with the nutrient diaphyseal system. There is no doubt that a large functional anastamosis
exists between the periosteal and nutrient system of vessels. 90,121 although controversy continues regarding the predominant vessel type connecting the two, the relative contribution of each system, and the predominant direction of blood flow.

VENOUS DRAINAGE OF BONE:

A great number of transverse and obliquely orientated venous sinusoids and larger tributaries enter into a large thin walled central venous sinus which courses vertically through the middle of the marrow cavity of the shaft in all long bones. 76;121 These tributaries deliver the venous side of the microcirculation into this large central collecting vein. The venous sinusoids of the metaphysis course vertically and parallel to the arterial branches to the growth plate. The sinusoids progressively coalesce ultimately forming a number of large metaphyseal tributaries which on joining together would seem to form each end of the central collecting sinus. 76;121

The venous blood may leave the bone by a number of routes. One or more large veins may leave the shaft through emissary foramina in the cortex, but as TRUETA 121 and MORGAN 76 stressed, the diameters of such foramina do not match the potential diameter of the central sinus. For this reason TRUETA 121 described the great potential of the intraosseous metaphyseal veins to drain into the surrounding soft tissue tributaries of the limb. This has been confirmed by intraosseous phlebography 115 Small emissary veins are occasionally seen traversing the cortex from the central sinus 19 but the role of the periosteal veins
remains a controversial issue. The degree to which the periosteum subserves the venous drainage of the cortex is central to the problem of the direction of cortical blood flow.

The principal epiphyseal venous sinuses traverse and leave the bony epiphysis in close proximity to the arteries.

THE MICROCIRCULATION OF BONE:

Morphologically the microcirculation within bone may be considered in three parts, depending on the location. Distinction may be found between the vessels in the cortex, the marrow and the juxta articular and juxta epiphyseal plate areas. This offers strong evidence in favour of functional specialization.

In the cortex the predominant vessel is a single capillary like structure of unusual length, and approximately 15 microns in diameter. The classical description of a vertical and transverse complex of arteries, veins and capillaries has now been challenged. The orientation of the capillaries is oblique and outwards through the cortex in a sunray-like pattern radiating from a point suggested to be the locus of the embryonic primary centre of ossification. Furthermore the concept of Haversian canals containing multiple vessels, both arteries and veins is similarly questioned.

Within the marrow the pattern is principally sinusoidal. These sinusoids are modified capillaries with a single cell wall and absent basement membrane. On electron microscopic examination WEISS has observed the reticuloendothelial character of the cells constituting the sinusoidal wall and their phagocytic
properties. BLOOM and FAWCETT have described how these cells ingest carbon particles from infused india ink and migrate away from their position on the vessel wall. Whether these vessels are open or closed to the surrounding haemopoietic tissue is not yet settled. Electron microscopic evidence would support the concept of an intact wall with ultra structural openings. Erythrocytes have occasionally been observed constituting part of the vessel wall. Extravasation of blood was not associated with this observation however. The marrow sinusoids are in continuity with the cortical capillaries at the cortex - marrow interface. The sinusoids themselves coalesce to form larger venous sinusoids, sinuses and tributaries which empty into the large collecting sinuses within the diaphysis, metaphysis, and epiphysis.

**EPiphyseAL PLATE BLOOD SUPPLY**

The viability of the growth plate was thought to be dependent more on the epiphyseal vessels, but its functional integrity in contributing longitudinal growth to the metaphysis is dependant also on an intact metaphyseal blood supply. The question as to whether its growth in width is due to interstitial or appositional growth is unsettled but certainly the outer rim receives its nutrition from a system of small vessels adjacent to its covering peri chondrium.

Branches of the epiphyseal vessels pass through canals in the lamellated bone approaching the epiphyseal side of the epiphyseal growth plate and terminate close to the germinal
layer of cells by breaking up into a spur of vessels within the calcified matrix. Each spur has been observed to supply the equivalent of four to ten columns of proliferating palisading chondrocytes. These vessels do not penetrate into the uncalcified cartilage, but their close proximity to the germinal cells has prompted TRUETA to postulate an endothelial origin for the germinal chondrocytes.

A very similar and rich network of vessels constitute the subchondr al system in juxta articular areas. Precapillary arterioles have been observed to pass through the subchondral bone underlying articular cartilage, but again do not penetrate into the articular cartilage except in disease.

On the metaphyseal side of the growth plate, vertical terminal branches of the perforating metaphyseal and nutrient vessels approach the calcifying layer and hypertrophied layer. TRUETA described a single discrete loop for each column of degenerating cells. Furthermore he proposed an open vessel system at the terminal loop where the erythrocytes were in direct contact with the cartilage and entered the empty lacunae following disintegration of the chondrocytes. Other investigators propose a freely anastomosing sinusoidal system without the one column, one vessel arrangement. BROOKS and LANHEN did not find an open system at the terminal loop. Their electron microscopic findings suggested that a thin line of endothelim always separated red blood cells from the final transverse septum of the growth plate. ANDERSON and PARKER found both open and closed systems, but the former in the minority.
THE FEMORAL HEAD

BLOOD SUPPLY IN MAN:

Much data is now available regarding the extraosseous

course and intraosseous behavior of the blood vessels to the
femoral head. Hunter described the "circulus articuli

vasculosus" in 1743 and the work of Langer and Lexer
defined the epiphyseal-metaphyseal system. Close analysis of
the intraosseous pattern had to await considerable refinement
of the injection technique. Tucker, Trueta and
Harrison and Judet and his co-workers described the
course and contribution of the vessels within the head and
neck of the femur, with great uniformity. In particular we
are indebted to the magnificent work of Trueta and his colleagues
for the present status of our knowledge.

EXTRAOSSEOUS: The medial circumflex femoral artery is the
principal source of blood supply to the femoral head and most
commonly derives from the profunda femoris. The medial
circumflex almost immediately passes posterolaterally between
ileopsoas and pectineus to reach the inferior part of the
femoral neck. In this extra-capsular position it supplies
branches to the lesser trochanter, the surrounding muscles, a
common but variable communication to the acetabular branch of the
obturator artery and a number of important vessels which pierce
the postero-lateral attachment of the capsule and pass up the
postero-inferior aspect of the femoral neck as retinacular
arteries.
The main circumflex vessel continues up behind the femoral neck supplying further retinacular branches to the posterior neck, but the most important vessels arise within the superior trochanteric notch. These pierce the capsule and course medially along the superior aspect of the femoral neck under the reflection of the synovium and capsule.

The lateral circumflex femoral artery which passes anterior to ileopsoas is responsible for a variable number of retinacular arteries which pass medially along the anterior aspect of the femoral neck.

Within the capsule, all the retinacular vessels partake in the "circulus vasculosus" and from which two distinct systems of vessels are seen to supply the femoral head. One, an inferior group, enter the inferior neck in two locations, medial and lateral, the medial vessels entering quite close to the inferior articular margin. A superior group similarly supply medial and lateral perforating metaphyseal vessels but two to six distinct arteries continue medially and enter the supero-lateral part of the femoral head and are known as lateral epiphyseal arteries. The distinction between epiphyseal and metaphyseal vessels is most clear in growing bones, when the growth plate clearly separates them. Before skeletal maturity the supero-lateral epiphyseal vessels enter the femoral head across the superior rim of the growth plate. CROCK believes that the anterior and posterior retinacular arteries are significant routes of blood supply to the femoral head.

The significance of the ligamentum teres vessels remains a vexing problem to anatomists and orthopaedic surgeons alike.
The bulk of evidence based principally on dissection, histological and injection studies, would support their patency in the adult, although some investigators claim their contribution to the femoral head diminishes with age. TRUETA examined thirty-six femoral heads from separate cadavers and found no diminution in the richness of the intraosseous arterial tree with age. WERTHEIMER in a microarteriographic and histological study of eighty seven cases found no evidence of variation in size of the ligamentum teres vessels with age. His results inferred that in two thirds of cases the vessels were less than 200 μ in diameter and so perhaps incapable of contributing significantly to the circulation over and above the fovea centralis. Patent vessels were demonstrated in all cases however.

Whatever contribution the ligamentum teres vessels may make to the femoral head viability, there seems little doubt they are important routes of revascularization should the femoral head suffer ischaemic necrosis.

**INTRAOSSEOUS:** The femoral head in man constitutes approximately two-thirds of a sphere, but bissection in the frontal plane reveals that the growth plate (or epiphyseal scar) lies more horizontally than a line joining the superior and inferior margins (Fig. 1). Therefore the metaphysis makes up a considerable proportion of the infero-medial femoral head. In adults the femoral head is seen to have distinct epiphyseal and metaphyseal systems of vessels with an intercommunicating
Figure 1: (a) Radiograph. Section of the adult human femoral head and neck in the frontal plane. (b) Diagrametic illustration of the metaphyseal (M) and epiphyseal (E) constituents of the femoral head. Line 'a' joins the superior and inferior articular margins. Line 'b' indicates the "epiphyseal scar".
system of vessels of varying size and number.\(^{31,125}\)

**THE FEMORAL HEAD EPIPHYSIS:** The organization of blood vessels within the capital epiphysis as defined by TRUETA and HARRISON\(^{125}\) has now gained universal acceptance. The lateral epiphyseal arteries, derived from the superior retinacular arteries, enter the epiphysis between the epiphyseal scar and superior articular margin. They then course downwards and medially in a gentle curve towards a point half-way between the fovea centralis and inferior articular margin (Fig. 2). The medial epiphyseal vessels run laterally in a horizontal line from their point of entrance at the fovea and richly anastomose with the lateral vessels en route. Numerous branches from these vessels radiate predominantly and directly towards the articular surface forming ever increasing but smaller arcades by virtue of their rich anastomoses. These branches tend to leave the parent stem and approach the articular surface at right angles. In the subchondral area, a rich system of subchondral loops is formed. Some branches pass through the honeycombed subchondral plate of cortical bone to reach the basal calcified layer of articular cartilage.\(^{19}\)

**THE FEMORAL HEAD METAPHYSIS:** This area is supplied principally by the medial group of inferior perforating metaphyseal arteries which enter close to the inferior articular margin and course vertically into the femoral head. (Fig. 2) The most medial of the superior perforating metaphyseal arteries commonly makes an abrupt medial turn on reaching the mid-point of the femoral neck and coursing into the femoral head shares the supply of the infero medial (or metaphyseal) part with the inferior vessels.\(^{59}\) (Figure 2).
18.

The metaphyseal arteries supply the metaphysis by a simple branching system of vessels in contrast to the vascular arcades seen within the epiphysis. The intraosseous course of the epiphyseal and metaphyseal vessels is not influenced by the trabecular outline or organization, but seems more influenced by the factors governing their formation in utero. The morphology of the microvasculature within the cancellous spaces depends on the degree of haemopoeisis present and this varies with age. In haemopoetic marrow they form a prolific meshwork of profusely anastamosing wide sinusoids. Within fatty marrow the more common outline of capillary networks is reproduced.
Figure 2: Microarteriogram of the proximal adult human femur. The lateral epiphyseal vessels enter the femoral head under the superior articular margin and traverse the epiphysis in a gentle curve towards a point half-way between the fovea centralis and inferior articular margin. Medial epiphyseal vessels are not apparent in this section. Inferior metaphyseal vessels enter close to the inferior articular margin and share the supply of the femoral head metaphysis with a superior metaphyseal artery which is seen to turn abruptly medially on approaching the mid-femoral neck.
DEVELOPMENT AND VARIATION WITH AGE:

GARDNER and GRAY\textsuperscript{43} and TRUETA\textsuperscript{120} have described how blood vessel containing tunnels appear within the cartilage anlage of the capital epiphysis during the ninth week of intra uterine life. The manner in which they develop, whether by inclusion or invasion is not certain, but their function is nutritional. With development these cartilage canals become more complex and extensive, and during the third trimester bear a close resemblance to the epiphyseal system of vessels seen after birth. Both horizontal superolateral and vertical inferior patterns appear, and are destined to become the future lateral epiphyseal and inferior metaphyseal systems respectively. This arrangement has been demonstrated by the injection technique in a foetus of 22 centimetres crown to rump length,\textsuperscript{19} and TRUETA described its constancy following examination of fourteen well-perfused foetuses and stillborn children.\textsuperscript{121} Each canal contains one afferent and one efferent vessel with a communicating tuft of capillaries.\textsuperscript{19,120} There is no anastomosis between the horizontal and vertically orientated canals.

Ligamentum teres vessels have been demonstrated during the third month of intra-uterine life\textsuperscript{43} and similarly observed to increase with age. They did not however extend to any significant depth into the epiphysis.

TRUETA\textsuperscript{120,121} described five phases in the development of the blood supply to the human femoral head, based on microarteriographic examination of forty six cases during the growth period.
1. FOETAL: This he defined as the intrauterine pattern which persisted until appearance of the secondary centre of ossification within the femoral head at four to six months following birth.

2. INFANTILE: From six months to four years the changes were two fold. During the first 2 years the ligamentum teres vessels regressed, and during the second two years, with advancement of the growth plate up the neck of the femur, the inferior metaphyseal vessels also began to regress.

3. INTERMEDIATE: at approximately four years of age the growth plate reached its definitive position within the femoral head and offered a staunch barrier to the inferior metaphyseal vessels. No vessels crossed the growth cartilage and the ligamentum teres vessels did not enter the epiphysis. Consequently the capital epiphyseal viability was almost totally dependant on the lateral epiphyseal vessels.

4. PREADOLESCANT: The ligamentum teres vessels returned and anastomosed with the lateral epiphyseal vessels. This medial epiphyseal system however, along the ligamentum teres remained variable and small.

5. ADOLESCANT: epiphyseal - metaphyseal intraosseous connections were formed following obliteration of the growth plate, but were variable in number, and at the small arterial level.
VENOUS DRAINAGE OF THE FEMORAL HEAD
In vitro\textsuperscript{125} and in vivo study\textsuperscript{48, 55} has demonstrated that venous drainage parallels arterial supply. The medial and lateral epiphyseal veins, and superior and inferior metaphyseal veins drain into the obturator, circumflex femoral and gluteal vessels.

COMPARATIVE ANATOMY OF THE FEMORAL HEAD BLOOD SUPPLY
The basic patterns of the blood supply to long bones in man, are similar in other mammals. TRUETA\textsuperscript{121, 127} in considering the vascular pattern in a wide variety of species including man, monkey, pig, dog, cat, rabbit, guinea-pig, hen and the rat concluded that "the basic arrangement of the vasculature of bone in all the animals studied is so similar to that in man that many of the small details in sinusoids and capillaries found in the dog and rabbit can not be distinguished from those encountered in human specimens."

FITZGERALD\textsuperscript{38} examined the blood supply to the femoral head in forty dogs using microarteriography. He demonstrated both medial and lateral epiphyseal vessels and communicating metaphyseal vessels after obliteration of the growth plate. The anatomy therefore closely resembled that in man. HAWK and SHIM\textsuperscript{53} confirmed the comparative anatomy in their preliminary microangiographic study of the canine femoral head following traumatic dislocation and epiphyseal separation (Fig. 3) A close similarity has also been demonstrated in the pig, especially before skeletal maturity.
The vascular anatomy of the femoral head in the rabbit will be presented in detail as it forms the subject of the experimental model in this thesis. The features described are based on the gross and microscopic anatomy as documented by LEMOINE and by TRUETA respectively, supplemented by pilot investigations prior to this study.
Figure 3: India ink (a) microarteriogram of adult proximal canine femur and (b) microangiogram of immature canine head and neck of femur. Note the close similarity of (a) to the human pattern (Figure 2). The growth plate in (b) offers an effective barrier to epiphyseo-metaphyseal connections. This barrier is not seen in adult case.
The growing rabbit is identical with man in possessing a distinct and separate vascular anatomy of the femoral head. A large vessel, arising from the deep femoral artery, and equivalent to the medial circumflex femoral artery in man, descends between the pectineus and ilio-psoas muscles and divides into a number of branches on reaching the infero-medial portion of the femoral neck. Some of these branches richly anastomose with the adjacent obturator and gluteal arteries.

Three principal vessels may be constantly delineated in this region stemming in whole or part from the medial circumflex artery.

1). An anterior branch which ascends anterior to the femoral neck, close to the outer attachment of the joint capsule. This vessel supplies a number of twigs destined to become anterior retinacular arteries and partake in the circulus vasculosus.

2). A posterior branch commonly arising from a coalescence of medial circumflex, obturator and gluteal vessels, which accompanies the external rotators of the hip to the posterior trochanteric notch. This vessel plays a large role with other vessels in the region, and with the nutrient diaphyseal artery in supplying the greater trochanter, the base of the femoral neck, and the upper diaphysis. (Fig. 4)

3). The most important branch, a small vessel which passes under the femoral neck and almost immediately pierces the capsule postero-inferior to the neck. It directly ascends the neck under a distinct mound of synovial
and fibrous tissue. This postero-inferior artery supplies branches to the circulus vasculosus, further branches to the proximal metaphysis, and finally as the main continuation plunges deeply into the capital epiphysis at the junction of the growth plate and femoral neck. (Figures 4 & 5). This artery therefore constitutes a true nutrient vessel to the epiphysis and corresponds to the lateral epiphyseal vessels in man. It is the principal route of blood supply to the femoral head in the rabbit.

The metaphysis, unlike that in man, receives a sizeable contribution from the terminal radicles of the nutrient artery to the shaft, subsidized to a varying extent by perforating metaphyseal arteries from the circulus vasculosus. (Fig. 6)

Within the epiphysis the postero-inferior epiphyseal artery divides repeatedly. The branches richly anastomose and pass forwards in fan-shaped fashion roughly parallel to the growth plate, forming a gentle arc convex medially. Four main branches of the original postero-inferior artery terminate within the anterior epiphysis. Short branches of these vessels, difficult to visualize, feed into the rich sinusoidal network of the cancellous spaces. Long radial branches run towards and perpendicular to the articular surface and terminate in a brush-border like complex of subchondral terminal arteriôles and capillaries. The efferent end of this subchondral system coalesce with the venous sinusoids of the
Figure 4: Microarteriogram of the proximal rabbit femur. Note the large posterior branch of the medial circumflex artery approaching the posterior trochanteric notch. The postero-inferior nutrient vessel to the capital epiphysis ascends the postero-inferior aspect of the femoral neck.

Figure 5: Higher magnification of the posterior aspect of the rabbit femoral head and neck seen in Figure 4. The postero-inferior artery to the capital epiphysis is seen in more detail.
Figure 6: Microarteriograms of the rabbit femur. Note the entrance of the diaphyseal nutrient artery into the proximal one third of the femur and its ramifications within the shaft. The vessels surrounding the upper femur in (b) are illustrated in higher magnification in Figures 4 and 5. Note the terminal radicles of the nutrient artery entering the femoral neck in (a). The dark blue stained vessels in (a) are collecting venous sinuses.
cancellous spaces (Fig. 7) and share with them the large friable venous sinuses of the epiphysis. The epiphyseal veins retrace in a transverse fashion the route taken by the afferent vessels and egress as one to three large veins at the postero-inferior os.

A juxta epiphyseal system of vessels identical with those in man, pass through the canals of the epiphyseal bone plate to supply the epiphyseal side of the growth cartilage. On the metaphyseal side the process of endochondral ossification is carried on by terminal radicles of the nutrient diaphyseal artery and more peripherally, the perforating metaphyseal arteries.

The importance of the ligamentum teres vessels in rabbits is uncertain. The results of selective interference with these vessels, which will be presented later, suggest they are a significant route of blood supply to the femoral head in very young rabbits only.

Maturity and closure of the growth plate allows free epiphyseal-metaphyseal vascular communication. (Figure 8). This is most obvious on the efferent side where with age the venous sinus connections may reach enormous proportions.

The diaphysis is supplied by one or more nutrient vessels originating from the equivalent of the lateral circumflex artery in man. These nutrient arteries enter the medial margin of the shaft in its upper one third and divide into superior and inferior branches on reaching the marrow cavity. (Figure 6). Thereafter they behave as in man and other animals.
Figure 7
High magnification Chinese ink microangiogram of the juxta articular vascular system of the rabbit femoral head. Coalescence with the sinusoidal networks with the subjacent cancellous spaces is seen in the lower part of the illustration.
Figure 8: Chinese ink microangiogram of (a) immature and (b) adult rabbit femoral heads. The dye has advertantly crossed the capillary bed and so filled both the afferent and efferent microvasculature, therefore the larger intraosseous vessels are obscured. Note the effective barrier to epiphyseal-anastomoses by the growth plate in (a)
The blood supply to the femoral head therefore compares well in man and rabbit. Both are dependant on an epiphyseal system of vessels especially before skeletal maturity. These vessels differ principally in the intra-capsular course they take to enter the femoral head. In both the growth cartilage offers a staunch barrier to epiphyseal-metaphyseal vascular connections. With maturity this barrier disappears (Figure 8).

In man the ligamentum teres vessels regress in early childhood and return in preadolescence to play a variable role in supplying blood to the capital epiphysis. Although their importance in maintaining viability of the human femoral head following injury is uncertain, they are an important avenue of revascularization in man as has been demonstrated by SEVITT, and by CATTO. In the rabbit also it would seem (from evidence to be presented later) the ligamentum teres vessels diminish in importance in late immaturity, and contribute less than 20% of the blood flow to the femoral head in adulthood. Their role in revascularization has been demonstrated in very young rabbits by LEMOINE, but not studied in adult animals.

FUNCTIONAL IMPORTANCE OF THE EPIPHYSEAL VESSELS IN MAN

Non-inflammatory or aseptic necrosis of the femoral head following fractures, of the femoral neck is the most common, and indeed important example of the functional importance of these vessels in man. AXHAUSEN and PHEMISTER separately described the true ischaemic nature of this complication, and it is generally believed that damage to the superior retinacular vessels is the principal factor in its genesis.
TRUETA examined the uninjured femoral heads of fifteen cadavers with technically acceptable microarteriographic results. The lateral epiphyseal vessels supplied approximately four fifths of the epiphysis in seven specimens, two thirds in a further seven and a little over half in one. SEVITT investigated the relative contribution of the various possible routes of blood supply to the femoral head in fifty seven cadavera, using microarteriography. Before injection he selectively obliterated all but one avenue of blood supply in each case. He found that in six specimens with the superior retinaculum alone intact, all or nearly all of the head was injected. In eight cases with the inferior retinaculum alone intact, only one showed filling of more than one third of the femoral head. It would seem therefore, we have abundant clinical and experimental evidence to support the importance of the intracapsular or retinacular vessels.

Interference with the extracapsular epiphyseal vessels diminishes in effect the further away from the joint this injury is caused. JUDET and his coworkers in a microarteriographic study using cadaver, failed to prevent filling of the retinacular vessels by ligation of the medial and lateral circumflex arteries at their origin alone. This is not surprising in view of the rich arterial anastomoses between the medial circumflex, obturator and gluteal vessels demonstrated on gross dissection by HOWE. MUSSBICHLER demonstrated significant connections between the inferior gluteal and posterior capsular arteries in five of fourteen normal volunteers who underwent selective internal iliac arteriography. In two of these the posterior capsular artery seemed to arise solely
from the inferior gluteal. Complete capsulectomy however consistently prevented retinacular filing in JUDETS study and in nine cases followed by MUSSBICHLER who demonstrated preoperative arrest of circulation in the posterior capsular vessel following fracture of the femoral neck, seven developed avascular necrosis of the femoral head.

**FUNCTIONAL IMPORTANCE OF THE EPiphySEAL VESSELS IN RABBITS**

The importance of the epiphyseal system of vessels in maintaining viability of the femoral head in animals is now well established. Interference with these vessels may be achieved by a number of methods including subcapital osteotomy or experimental epiphyseal separation by incision, stripping or ligation of the femoral neck, or by selective vascular damage such as interference with the ligamentum teres vessels, or the nutrient vessel to the epiphysis, that is the postero-inferior artery. Generally speaking, damage to the retinacular vessels, with or without ligamentum teres injury, is followed by epiphyseal bone death in young animals. The growth plate renders the blood supply to the epiphysis more precarious and effectively hinders revascularization from the femoral neck. In adult animals the intraosseous epiphyseal-metaphyseal anastomoses may offer an alternate route of blood supply and drainage but this has been insufficiently studied. Selective interference with the ligamentum teres vessels has met with variable results. In rabbits the changes
induced were inversely proportional to the age of the animal and epiphyseal bone death was not found in adults. STEWART failed to produce significant and consistent avascular necrosis in six-week old rabbits and ZEMANSKY and LIPMANN produced necrosis by ligamentum teres ligation in rabbits less than seven weeks old only. The data dealing reported changes following ligamentum teres damage is however difficult to interpret as a satisfactory ligation or division must involve an arthrotomy and at least transient subluxation or luxation. The earlier reports do not indicate that "sham" procedures were carried out on the control side. The bone death may therefore have resulted from the capsulotomy, transient subluxation or luxation, or the ligamentum teres damage per se.

SHIM quantitated the contribution of the ligamentum teres vessels to epiphyseal blood flow as 17% in adult rabbits.

LEMOINE selectively divided the posteroinferior artery to the capital epiphysis, within the joint capsule. Each one of sixteen young rabbits developed some changes detectable on radiographic, histological or macroscopic examination. Microarteriography revealed an avascular femoral head during the first week revascularization through the ligamentum teres and metaphyseal arteries during the second week, hyper-vascularity during the third and gradual return to normal thereafter. It is interesting to note that interference with the stem vessels outside the joint capsule was largely without effect on epiphyseal viability. This is in keeping with the work of JUDET and his associates in man.
Interference with the epiphyseal blood supply may be induced also by experimental microembolization using carbon or sodium morrhuate particles. The lesions are not specific for the epiphysis however and have been produced in the diaphysis and metaphysis with equal ease using carbon and septic emboli. This is similar to the non-specific lesions following suggested micro-embolization in man, as seen in Caisson's disease.

Epiphyseal ischaemia may be produced in dogs and pigs by prolonged forced hip joint splintage in an unphysiological position. It has been suggested that prolonged increase in the intraarticular pressure is the mechanism responsible. SALTER has however interpreted the changes as due to intraepiphyseal interference with perfusion, induced by distortion of the soft and maleable cartilagenous femoral head in young animals. The same effect may however be produced by directly increasing the intraarticular pressure via an indwelling catheter. Significant interference with epiphyseal perfusion may be incurred by pressures as low as 50 mmHg in the young pig, and 75 mmHg in puppies. This would suggest a tamponade effect on the retinacular vessels, perhaps leading to venous gangrene of the femoral head.
DRINKER, DRINKER and LUND pioneered the truly objective study of bone blood circulation with their perfusion studies in dogs and other animals. The principles underlying such investigation and the sum of knowledge so far gained were comprehensibly reviewed by SHIM. He classified the possible methods of investigation as follows:

I QUANTITATIVE STUDIES.

A. Direct Methods.
   1. Cannulation - collection measurement
   2. Application of electromechanical flow meters

B. Indirect Methods.
   1. Blood tissue exchange mechanism
      a. Fick principle
      b. Radioisotope clearance
   2. Indicator-dilution principle.
      a. Radioisotope (Cr⁵¹, I¹³¹)
      b. Dye (Evans blue)
   3. Venous occlusion Plethysmography

II Qualitative Studies

A. Flow Pattern
   1. Vital microscopy
   2. Bone venography
B. Selective arterial isolation to determine relative importance of arteries.

1. Destruction or occlusion of certain vessels
   a. Study of devitalized area
   b. Effect on fracture healing or bone growth.
   c. Effect on relative isotope uptake

2. Injection of indicators into an artery to observe the area it sustains.

C. Bone hemodynamics

1. Direct methods (cannulation)
   a. Assessment of relative flow volume change
   b. Study of arteriovenous blood constituents.

2. Indirect Methods.
   a. Intramedullary blood pressure
   b. Intra osseous thermometry
   c. Oxygen tension of bone
   d. Radiosotope uptake or clearance from bone

D. Alteration of hemodynamics to stimulate growth, fracture repair and bone vitality.

1. Sympathectomy
2. Arteriovenous fistula
3. Periosteal stripping
4. Fracture
5. Ligation of a major vein
6. Application of low pressure tourniquets
7. Artery or muscle transplantation to bone.
COPP and SHIM described an indirect method of assessing bone blood flow using the clearance by bone of a circulating bone-seeking radioisotope. SHIM applied this method extensively to the quantitation of bone blood flow and its controlling factors in animals, and with COPP and PATTERSON described the rate of blood flow in canine and rabbit bones as approximately 10 ml/min/100gms fresh weight. Corrected for the extraction ratio of Sr, and the relative percentage of total body weight contributed by the endoskeleton they estimated that total skeletal flow accounted for 7% of the resting cardiac output in these animals.

SHIM and his associates applied the same technique to the lower limb of a 24 year old male about to undergo a high thigh amputation for localized malignant bone disease. Bone blood flow was estimated at 2.5 ml/min/100gms wet bone in this patient and total skeletal flow at 6.3% of the resting cardiac output. This compared well with skeletal blood flow in dogs and rabbits.

DRINKER et al also suggested that blood circulation in bone was controlled by hormonal, metabolic and neuronal factors. There is ample evidence to support this hypothesis today. It has been demonstrated that stimulation of the sciatic nerve in adult rabbits reduces bone blood flow in the hind limb. This was measured directly using the nutrient vessel cannulation technique, and by monitoring intramedullary pressure. Furthermore section of the sciatic nerve increased the rate of bone blood flow by 5 to 45% with 14 days. This increase was maximal in the foot bones.
that experimental haemorrhagic shock caused a fall in bone blood flow, and its relationship with systemic blood pressure suggested a vasomotor tone increase in intraosseous peripheral vascular system. Dibenzyline abolished this vasoconstriction suggesting that the vasomotor effects of shock on bone blood flow were largely mediated through an alpha receptor system.

The effects of norepinephrine, epinephrine, acetylcholine, and pitressin have been quantitated in experimental animals. Microgram doses of epinephrine reduced the rate of bone blood flow by 25 to 75%. HAWK and SHIM, HAWK, and YU have perfected the use of intramedullary pressure monitoring as a tool in studying directly the quantitative and qualitative aspects of blood flow. Their work further confirmed the hormonal effects of blood flow. Adrenaline and noradrenaline caused a profound fall in intramedullary pressure associated with a decrease in bone blood flow. The site of action whether extra- or intraosseous was not clear, but the pressure effects in bone were independant of the systemic effects of the hormones.

There is evidence to suggest that metabolic factors are the most important overall controlling mechanisms. Systemic hypoxia induced by rebreathing has been demonstrated to increase bone blood flow in the rabbit and local increase in \( pCO_2 \), acid metabolites and reduced pH exerted a similar effect, typified by the prolonged hyperaemia following temporary femoral artery occlusion. More important, this hyperaemia was not abolished by nerve stimulation or vasopressor hormones.
Obviously therefore metabolic factors may over ride other controlling mechanisms.

THE FEMORAL HEAD:

The physiology of blood circulation within the ends of long bones is not well understood. The many channels taken by the epiphysio-metaphysial vessels, and the further variation which must be incurred by skeletal maturity and obliteration of the growth plate personifies the difficulties which bone as an organ in general presents to the investigator.

MATUMOTO and MIZUNO\textsuperscript{73} using the clearance rate of a radiopaque dye directly injected into bone, estimated the rate of blood flow in the femoral head of a normal adult man to vary 3 to 7 ml/min/cu. cm. of bone.

SHIM and his associates\textsuperscript{107} using the bone clearance of circulating Sr discovered a significant difference in the regional flow rates in the femur of 50 adult rabbits. Bone blood flow within the femoral head was 18.5 ml/min/100 gms. fresh weight. This contrasted with 7.5 ml/min/100 gms. fresh weight in the shaft. Using a similar technique the same workers investigated the regional contribution of the nutrient artery to the femur in adult rabbits.\textsuperscript{108} Obliteration of the diaphysial nutrient artery caused a reduction of 37% in the flow rate within the upper femoral epiphysial and metaphysis. It was concluded that under normal conditions the epiphysesio-metaphysial vessels are responsible for 63% of the bone blood flow within this region.
MILES measured the intramedullary pressure in the femoral head of over 30 patients following intra and extracapsular fractures, following reduction of traumatic dislocation and in some normals. The pressure varied and sometimes rose to 50 ml. saline. He stressed the normal fluctuation with arterial pulse pressure and rate, and suggested that loss of this conducted pulse wave following trauma was indicative of an ischaemic femoral head.

STEIN and his co-workers demonstrated a significant difference between the mean diaphyseal and epiphyseal intramedullary pressures in dogs (50:12 min Hg). There was a similar but greater discrepancy in pulse pressure (8.1 min Hg). The significance of these observations is not clear. BROOKS has suggested that the circulus vasculosus serves a purpose in lowering the blood pressure within the epiphyseal arteries before they enter the bone. He furthermore interpreted the metaphyseo-epiphyseal, and epiphyseo-joint space pressure differences as an indication of unidirectional flow of nutrients from metaphysis to epiphysis and epiphysis to joint space. This, if correct, would support his contention that growth-plate viability is dependant on the metaphysis, and articular cartilage viability dependant on the epiphysis, both somewhat controversial and unorthodox views.
REVIEW OF THE LITERATURE

TRAUMATIC DISLOCATION OF THE HIP

CLINICAL:
   Classification
   Adults
   Children
   Avascular Necrosis

EXPERIMENTAL
TRAUMATIC DISLOCATION OF THE HIP

The serious implications of this injury to the principal weight-bearing joint in man were well emphasized in a recent editorial. "Of the known causes of unilateral osteoarthritis of the hip, traumatic dislocation of the hip joint, by involving characteristically the young working male, can be responsible for not only great pain and disability, but grave economic loss as well". The overall incidence is unknown, but would obviously depend on the life style of the population under consideration, as it is characteristically associated with high impact injury. BRAV described the incidence as 5% of all joint injuries, but did not clarify his source. Although the incidence of hip dislocation has steadily risen with the speed and complexity of transport, it remains an uncommon injury, especially in childhood, and statistically significant appraisal of the overall outcome and its salient contributory factors has had to await co-operative, combined and long-term study. A number of such reports have now been documented and these will be reviewed.

CLASSIFICATION:

The femoral head may displace over the lip of the acetabulum or through its floor, into the pelvis. The latter is described as a central fracture dislocation and considered as a separate, or predominantly acetabular injury, by most authors. One series of 193 dislocations included an incidence of 14% central fracture dislocations. This review will not deal with the outcome of central displacement.
The dislocated hip is generally classified by type and group. The type may indicate the route taken by the luxating femoral head, or more commonly describe the position of the displaced head at the time of diagnosis, and so posterior, anterior, obturator and perineal. Anterior dislocation accounts for 10 to 12% of such injuries, while the obturator and perineal types are rare. The grouping is based on the presence and degree of bone damage around the hip, and the number of groups used varies from author to author.

BRAV, reporting on 523 dislocations, used three groups:

- Group I: simple dislocation
- Group II: dislocation with associated fracture of the acetabular rim.
- Group III: Dislocation with associated fracture through the acetabulum or femoral head.

Over one thousand cases have been reported by seven authors within the last twenty years, and more than half of these were suitable for close analysis and follow up. Furthermore MORTON reviewed 825 cases from the literature with particular stress on the complications.

The injury is most common during the third and fourth decade and in the population at large males are affected three times more commonly than females. Although varying from series to series, the left and right hips are equally affected overall. Characteristically the dislocation is suffered in a motor vehicle accident and associated with bone damage to the femoral head or acetabulum.
THOMPSON and EPSTEIN reported 204 cases. 116 were suitable for follow-up. On clinical and radiological evidence, the outcome was closely related to the severity of the injury as judged by the degree of bone damage. (Table 1). Of 78 patients with a fair or poor result, only 10 had suffered a simple dislocation. An insufficient number underwent delayed reduction to draw any conclusions related to the duration of dislocation. The adult age and length of time before unprotected weight bearing did not influence the results.

STEWART and MILFORD reported 193 cases, 123 of which were available for follow-up. The clinico-radiological outcome was again closely related to the severity of injury (Table 1). None of their cases reduced after 24 hours had a satisfactory result, but all of these patients had associated bone damage. The age did not affect the outcome.

MORTON reported 62 cases. In 48 followed up, the influence of bone damage was similar to earlier reports. Excellent results were gained only in those reduced in less than twelve hours. The duration on non-weight bearing did not seem to affect the outcome.

BRAV reported 523 dislocations. Satisfactory analysis was possible in 264. The severity of injury and outcome again closely correlated. Delay in reduction past 12 hours was associated with more than a two-fold increase in unsatisfactory end results. He reported on 66 anterior dislocations, 15% of which were ultimately unsatisfactory.
COMPLICATIONS IN ADULTS:

Recurrent dislocation: 1.5% 16:77
Myositis ossificans: 2% 77:117:118
Sciatic nerve palsy: 12 to 16%, most common and severe following associated bone damage.

TRAUMATIC ARTHRITIS: This is the most common cause of unsatisfactory functional recovery. As earlier reviewed, it is closely related to the severity of injury and the duration of dislocation. Avascular necrosis of the femoral head is a common accompaniment and it is frequently difficult to differentiate the two. This may account for the exceptionally low incidence of avascular necrosis following traumatic hip dislocation recently reported by HUNTER and LAMPKE at 2% and 7% respectively.

AVASCULAR NECROSIS: For later discussion.

CHILDREN:

Traumatic dislocation is distinctly less common in childhood. The male preponderence is again 3:1 (combined 78 and 84). Anterior dislocation occurs in 7 to 16% of cases, while central dislocation is uncommon or unreported. The recorded complications are associated fractures, epiphyseal separation, premature closure of the growth plate, recurrent dislocation, coxa magna, traumatic arthritis and avascular necrosis. Permanent sciatic palsy has not been reported.
The first large-scale review was documented by Morton. He reported 136 cases following extensive review of the literature, and addition of 7 new cases. The mechanism and severity of the injury, and duration of dislocation had been poorly recorded in the literature and conclusions were consequently difficult to make.

Glass and Powell reported on 108 cases following similar literature review and addition of 47 new cases. Only 25% of their cases had been associated with a possible high impact injury. They stressed the trivial nature of the injury frequently seen in childhood. They could find no corelation between the severity of injury, and the type and incidence of complications.

Funk reported 40 new cases, and was the first to subgroup this injury and its outcome on the basis of age. He stressed the close relationship between age above 5 years, and the severity of injury. He concluded that this relationship was based on the ease with which the hip may be dislocated in very young children. Duration of displacement considerably influenced the ultimate radiological outcome, but age had a similar influence even if the dislocation was reduced with 24 hours.

The Pennsylvania Orthopaedic Society presented the most comprehensive and recent report available, with 165 patients, including 51 personal cases. They found a clear connection between severity of injury and ultimate clinico-radiological outcome. Severe injury as judged by the mechanism or circumstances of the accident and x-ray findings, was associated
with a 3 fold increase in clinico-radiological dissatisfaction. In their personal series 18% had accompanying bone damage around the hip. Seven of these cases were followed to maturity and 6 of them classed as unsatisfactory results. As in FUNK's series nine years seemed the critical age limit. 90% of these cases reduced within 24 hours gained an excellent or good result. This fell to 44% following delayed reduction. The authors stressed however that severe injury commonly influenced the duration of dislocation by hindering diagnosis, or of necessity delaying prompt treatment of the dislocation. The period of non-weight bearing did not clearly influence the outcome.

AVASCULAR NECROSIS OF THE FEMORAL HEAD FOLLOWING TRAUMATIC DISLOCATION OF THE HIP

It is generally believed that death in whole or part of the femoral head following traumatic dislocation of the hip in man, is incurred by interference with the blood supply. It was first, and almost simultaneously described as a complication of dislocation by BERGMANN, DYES, and STEWART on the basis of its clinical and radiological similarity to avascular necrosis following intracapsular fracture of the femoral neck documented earlier by PEMISTER and AXHAUSEN.

LAUFER reported the macroscopic and histological picture in a case of late segmental collapse of the femoral head following traumatic posterior dislocation. The features described and illustrated are indistinguishable from those constantly found in vascular necrosis following femoral neck
Indeed they are similarly comparable with the histological features of bone, necrosis within the tibia commonly associated with occlusive peripheral vascular disease.

The location and type of vessel damage or occlusion is not certain and it may understandably vary. Our knowledge of the particular vascular anatomy of the femoral head and the functional importance of the epiphyseal vessels, as presented earlier, would support extraosseous blood vessel damage as a reasonable supposition. The work of JUDET on cadavers and LEMOINE and ROKANNEN on rabbits indicates that such vessel injury close to the femoral head obviates collateral anastomotic compensation and causes significant embarrassment of blood supply to the femoral head.

Venous tamponade would seem unlikely as the capsular damage caused by dislocation would be expected to decompress intra-articular pressure. Intraosseous and extraosseous vascular occlusion is a further possible cause or contributory factor. The features of avascular necrosis following trauma are not distinct from those associated with Caissons disease in man, or microembolization in animals.

LAUFER described a case of delayed segmental collapse of the femoral head in a 13 year-old boy following blunt trauma to the hip without fracture or dislocation. This case could be cited to support a theory forwarded by STEWART and MILFORD, that avascular necrosis following traumatic dislocation may result from intracellular damage incidental to the force and counterforce imposed at the time of injury. It could, of course,
be more easily explained by assuming the tamponade effect of post-traumatic effusion which would interfere with the superior retinacular route of blood supply and drainage upon which the capital epiphysis is almost totally dependant in pre-adolescence.

INCIDENCE AND CONTRIBUTORY FACTORS:

ADULTS: MORTON reviewed 645 cases from the literature and found an incidence of 14%. In 48 new cases he estimated that avascular necrosis was certain in 17% and probable in 30%. The overall incidence is otherwise reported at 21%, 23% and 26%. Close analysis of the clinical material repeatedly stresses two salient contributory factors:

1. Duration of dislocation. All authors have implicated delay in reduction as a factor contributing to the incidence of avascular necrosis. In particular BRAV's figures suggest that delay beyond 12 hours is associated with more than a three-fold increase in the likelihood of bone death within the femoral head, regardless of the severity of the initial injury.

2. Severity of injury. Avascular necrosis following simple dislocation alone in adults falls to 10%, 11% and 15% (if reduced with 12 hours). Associated bone damage increased the overall incidence to 35% and if severe, such as fracture through the femoral head or acetabulum, to 70% in BRAV's series.
Age and duration before unprotected weight bearing does not apparently influence the incidence of avascular necrosis, although early weight bearing may affect the degree of associated bone collapse. Repeated attempts at closed reduction or open reduction does offer a poorer prognosis, but obviously by a multifactorial influence.

BRAV reported 66 cases of anterior dislocation of which avascular necrosis was 9%.

CHILDREN: Ischaemic necrosis of the femoral head occurs in 10% of children after traumatic hip dislocation. As in adults the incidence is considerably influenced by the duration of displacement and severity of the initial injury. The PENNSYLVANIA ORTHOPAEDIC SOCIETY closely analysed 20 cases of resulting avascular necrosis.

18 - had reduction delayed beyond 24 hours
14 - had suffered severe hip trauma
1 - had a recurrent dislocation

MORTON found 12 cases reported in the literature. The duration of dislocation was reported in 5 only, and 4 of these were reduced later 7 days from the time of injury. He furthermore found 7 cases with associated bone damage. Three of these developed avascular necrosis. PIGOTT reported 9 cases of traumatic dislocation in which one, a nine year old girl, developed ischaemic necrosis. She had fallen from a height of forty feet.
Avascular necrosis is rare as a complication in children less than five years of age, but so too is severe injury as the cause of dislocation in this age group.

Overall therefore, avascular necrosis of the femoral head may be expected to follow in up to 30% of adults, and 10% of children after a traumatic hip dislocation. The mechanism and severity of the injury, and duration before reduction considerably influence the outcome in this regard. It is well to remember however that severe injury is a common cause and accompaniment of delayed treatment. The influence of skeletal maturity is obviously personified by the greater likelihood of severe injury and associated fractures about the hip in adults. Considering simple dislocation alone in adults the incidence of ischaemic femoral head necrosis approaches that seen in children. This is surprising, as the more precarious blood supply to the capital epiphysis before skeletal maturity would lead one to expect a higher incidence in children. The influence of age in childhood is probably a result of the ease with which the hip may be dislocated below five years of age.

It is clear therefore that the factors of age if a child, skeletal maturity, severity of injury and duration of dislocation are largely inseparable and cannot be individually assessed on the basis of our clinical information alone.
EXPERIMENTAL DISLOCATION OF THE HIP IN ANIMALS:

As presented earlier, the functional importance of the epiphyseal vessels in maintaining viability of the femoral head in animals is now well proven. Avascular necrosis may be consistently produced by gross intra- or extraosseous damage to this system, or selective interference with the nutrient vessels to the epiphysis. The growth plate may increase the risk and extent of ischaemic bone damage in growing animals and certainly hinders revascularization after the fact of epiphyseal death has occurred.

In contrast the series of events following dislocation has received scant attention. No doubt many of the earlier reports dealing with selective damage to the ligamentum teres vessels infers at least transient subluxation or luxation.

LEMOINE ligated the ligamentum teres in 5 immature and 2 mature rabbits. Four of the growing rabbits developed radiological features of avascular necrosis associated in 3 with hypervascularity detected by microarteriography. The author stressed however that each case underwent postero-lateral arthroplasty and dislocation of the hip during the procedure. He made no conclusions.

ROKANNEN also recognized this problem and investigated the effects of ligamentum teres ligation and transient dislocation in 22 rabbits (age not stated). He found histological evidence of limited avascular necrosis in 4 animals.
Müller studied the effects of traumatic luxation of the hip in animals of various ages and was the first to describe the histological features following this injury. He described fibrous replacement of the marrow and scattered bone necrosis within the femoral head in adult animals.

Bergmann produced closed dislocation in 2 adolescent rabbits and noted limited subchondral bone necrosis in one animal sacrificed at 8 weeks.

Bohn conducted a radiographic, histological and microarteriographic study of the femoral head following manual posterior dislocation of the hip in 20 newborn rabbits, while investigating the dysplastic features of congenital dislocation of the hip. Ischaemic necrosis was constant and extreme. The capital epiphysis was rendered almost totally avascular and revascularization occurred from the trochanteric epiphysis and through the growth plate during the second week of displacement. The histological picture and vascular pattern returned to normal during the fourth week. He later reported the same series of events using tetracycline fluorescence as a measure of blood supply to the femoral head.

Smith investigated the gross alterations following operative luxation of the hip in pups. Considerable coxa vara was produced, but no histology undertaken. Sham arthrotomy was not carried out on the control side.

Rokanne induced sustained dislocation in 22 rabbits (age not stated) following arthrotomy. The animals were sacrificed at varying intervals up to nine months following injury. Segmental necrosis of the femoral head was noted in half the cases, and occurred as a late feature only.
Overall therefore the reported consequences of open or closed dislocation of the hip in animals varies with the investigator, and method of study and the age of the animal. A controlled study of the time sequenced events following dislocation has not been undertaken, nor an attempt to assess the influence of skeletal maturity, duration of displacement and reduction.
MATERIALS AND METHODS

The EXPERIMENTAL MODEL:

The comparative anatomy of the blood supply of the femoral head in man and the rabbit has been reviewed. The hip joint of the rabbit is a suitable model for studying the events following traumatic dislocation.

ANIMALS: A total of 220 New Zealand white (female) rabbits, 65 mature (averaging 3.98 Kg/m) and 155 immature (averaging 2.22 Kg/m) were used.

ANAESTHESIA: Intravenous nembutal 30mg. per kilogram. Maintenance doses were not required.

DISLOCATION: The left hip was manually dislocated in all cases by dorsally applied force along the line of the femur with the hip held adducted, internally rotated and in slight extension. The route and ultimate position of displacement was poster-superior. Successful dislocation declared itself by an audible and palpable click, postero-superior shift of the greater trochanter, and leg-length discrepancy.

REDUCTION: If planned, manual reduction was undertaken at the same, or a different sitting (under anaesthesia). Reduction was achieved by ventral traction along the line of the femur with the hip held in the same position as for dislocation.
The pelvis was stabilized with the left hand and the femoral head guided into the acetabulum with the left index finger. Palpable excursion of the femoral head into the acetabulum, and disappearance of the leg length discrepancy signified reduction. Fluoroscopic examination was carried out within 10 minutes in all cases. The animal was discarded from the study if a second attempt at reduction was needed.

All animals were returned to their cages following anaesthesia and allowed unrestricted activity and standard diet for the length of their survival.

CONTROL: The right hip was untouched in all cases and used as a control.

INVESTIGATION: The changes within the femoral head following dislocation, and reduction were assessed by three methods.

A. Microangiography
B. Histology
C. Radiography.

A. MICROANGIOGRAPHY

Under nembutal anaesthesia, and following a mid-line abdominal incision, the abdominal aorta and inferior vena cava (I.V.C.) were exposed. The aorta was ligated just distal to the renal vessels after injection of Heparin (1000 U per kilogram) and cannulated with a f8 polyethylene catheter. The
I.V.C. was allowed to bleed freely into the peritoneal cavity after proximal ligation (Figure 9).

Two solutions were infused sequentially at constant temperature (42 degrees C) and pressure (80 mm Hg).

1. Physiological saline (+ Heparin 1000U/litre) until the return through the I.V.C. was largely clear of blood.

2. Tracer Dye: 250 ml 20% Mannitol
   250 ml commercial Chinese ink
   500 ml water with 40 gms Gelatin.

The dye infusion was continued until the surrounding skin, serosa and organs indicated a satisfactory perfusion, This averaged six minutes. (Figure 10).

The animal was sacrificed with an overdose of nembutal, into the proximal I.V.C. during the saline infusion. The hind limbs were moved through a physiological range of movement during infusion.

The vessels were decannulated and tied. The animal was stored overnight in a fridge to form a gel of the Chinese ink-gelatin dye, and the following day the hind limbs were carefully removed after proximal vessel ligation. The macroscopic features in terms of the joint position, bone damage and deformity, and gross perfusion quantity and its extent were noted at this time (Figure 11). The proximal half of each femur with attached soft tissues was stored in 10% formalin.
Figure 9: The general set up of the infusion. Under nembutal anaesthesia two solutions (1. Saline & 2. The tracer dye) were sequentially infused into the abdominal aorta proximal to its bifurcation under standard conditions of temperature and pressure.
Figure 10: The bladder (a) before and (b) after satisfactory infusion with dye.
Figure 11. Posterior aspect of the proximal femora after dislocation of the left hip (to the left of the illustration) and infusion. Note the frayed ligamentum teres, and absence of dye perfusion in the soft tissues of the postero-inferior femoral neck and capital epiphysis on the left side.

Figure 12: The final preparation before stereomicroscopic analysis from one immature rabbit after dislocation of the left hip and infusion. The left capital epiphysis is almost devoid of dye perfusion (to the right of the illustration).
Figure 13: Closeup of the mid-sections of the (a) right and (b) left femoral heads presented in Figure 12. There is a profound perfusion deficit within the dislocated left capital epiphysis. The left metaphysis has perfused well, but the growth plate offers an effective barrier to perfusion of the epiphysis from this source.
This caused an irreversible gel of the dye, and fixed the tissues. Seven days later the soft tissues were carefully removed and the proximal 1/3 of each femur decalcified in R.D.O.* for four days, with constant agitation and at room temperature. The bone segments were then divided in the frontal plane into 1 to 2 mm. sections, bleached in Hydrogen Peroxide, dehydrated in 70 to 100% alcohol and cleared by the Spalteholz technique.

The final sections were each analysed by stereomicroscopy always in relation to the control side. At that time a composite map could be made of the location, extent, and quantity of dye perfusion, and its source. This final stage was undertaken on average, 4 weeks after sacrifice (Figures 12 & 13).

**EXPERIMENT I**

10 rabbits, 5 mature, 5 immature. (Table II)
Aim: to establish if infusion proximal to the aortic bifurcation before dislocation would result in quantitatively and qualitatively comparable perfusion of dye in the right and left femoral heads.

**EXPERIMENT II:**

95 immature rabbits (Table III)
Aims: to establish what changes would be apparent at 10 minutes after dislocation.

*MAYNARD DIAGNOSTIC, Ontario. Constituents not revealed.
2. to establish what changes would be apparent at 10 minutes after immediate reduction.
3. to study the sequential changes in dye perfusion of the femoral head at 1, 2, 3, 5 and 7 days after dislocation.
4. to evaluate how the changes following dislocation could be altered by immediate reduction, reduction at 24, and at 48 hours, as evidenced by the microangiographic picture at 1,3,5, and 7 days after reduction.

EXPERIMENT III:
20 mature rabbits (Table IV)
Aims: 1. to establish what changes could be observed 10 minutes after dislocation of the mature femoral head.
    2. to establish what changes would be apparent at 7 days after dislocation.
    3. to evaluate how the changes 7 days following dislocation could be altered by immediate reduction, and reduction at 24 hours.

EXPERIMENT IV:
10 rabbits, 5 mature, 5 immature (Table V)
Aim: to establish if reduction at 12 hours offered any improvement over reduction delayed to 24 or 48 hours, in terms of the microangiographic picture 7 days after reduction.

The early changes following unreduced dislocation, and immediate reduction were studied by manipulation of the hip after mid-line abdominal incision and atraumatic exposure of the aorta and inferior vena cava was carried out.
Thereafter, heparinization, cannulation and infusion could be achieved with an average delay of 10 minutes.

B. HISTOLOGY:

Each animal was sacrificed by intracardiac injection of 10% KCl. The hind-limbs were carefully detached, note being made of the macroscopic features (Figure 44). After in vitro x-ray, the proximal 1/3 of each femur was removed and bisected in the frontal plane. The specimens were fixed in a mixture of 100 parts 96% alcohol, 40 parts formalin, and 7 parts glacial acetic acid for 4 hours, decalcified in RDO* for 12 hours, and processed for haemotoxylin and eosin staining. Two 5 µ representative sections were taken from each half of each femoral head. One anterior, one posterior and two mid-sections were thus examined from each side.

Two major groups of animals underwent histological examination:

1. 60 long-term survival rabbits. (Table VI). The mismatched numbers of animals in each sub-group were incurred principally by deaths and complications.

2. 25 rabbits (Table VII)

This group represents 5 sub-groups of 5 animals each, chosen randomly from a larger number survived for 3 to 4 weeks.

* MAYNARD DIAGNOSTIC, Ontario: Constituents not revealed.
Figure 14: Anterior aspect of the right and left proximal femora after long-term unreduced dislocation of the left hip. Note the extreme coxa vara and antversion. Note also the abundant chondro-osseous tissue formation in the region of the lesser trochanter and inferior femoral neck.

Figure 15: Antero-posterior x-ray of the pelvis and hips within 48 hours of unreduced dislocation of the left hip.
C. **RADIOGRAPHIC:**

All animals intended for survival past 7 days were x-rayed with 48 hours of the last manipulation to the hip. (Figure 15). All animals that underwent reduction, and intended for survival past 7 days, were fluoroscoped 7 days after reduction to rule out delayed spontaneous redislocation. Thereafter repeat x-ray examination was planned at four week intervals in all cases.

It soon became obvious that the flexion-adduction contracture of the hip present at 4 weeks rendered comparable positioning of the right and left hips difficult, and possibly harmful to the reactive soft tissue and new blood vessel formation around the left hip. In vivo x-raying was consequently abandoned as an investigative procedure, and continued at 4 week intervals only in reduced animals to rule out redislocation. At such intervals an antero-posterior radiograph was taken with both hips lying in the preferential position of rest.

The upper femora were x-rayed in vitro after sacrifice and removal of the hind limbs, in all cases before bissection and processing for histology.
Figure 16: (a) Superior aspect of the left femoral head and neck.
(b) Sectioned in the frontal plane. Sections numbered 1 to 4, posterior to anterior.
(c) Anterior aspect of the separated segments.

Figure 17: (a). Anterior aspect of the separated segments of the femoral head and neck sectioned in the frontal plane. The solid dark filling indicates perfusion with dye.
(b). Transfer of information regarding the location and extent of perfusion to a map, using the superior aspect of the femoral head.
(c). The final diagramatic map. There is dye only within the postero lateral part of the femoral head.
Figure 18: Inclusion of (b) the anterior view of the posterior segment (No. 1) augments the information offered in Figure 17 (c) and Figure 18(a).

Figure 19: Semiquantitative analysis.
(a) perfusion equal, greater or slightly less than control
(b) perfusion considerably less than control
(c) no perfusion
(d) to the left, the anterior view of the posterior segment, and to the right, the superior view of the femoral head and neck. There is equal, greater or slightly less perfusion than control postero-laterally. There is no perfusion antero-medially. The intermediate area is considerably underperfused.
RESULTS

A. MICROANGIOGRAPHIC FINDINGS:

Stereomicroscopic examination of the perfused sections allowed a semiquantitative analysis of the location, extent, and degree and source of vascular filling within the femoral head. A composite map could be made in each case, and the information will be presented as illustrated in Figures 16, 17, 18 and 19.

EXPERIMENT I: (Table II)

Infusion of dye proximal to the aortic bifurcation in uninjured mature and immature animals consistently yielded comparable perfusion of the femoral head on right and left sides. A slight quantitative difference was on occasion observed between the individual sections. This was a uniform discrepancy in all cases and principally due to slight differences in section thickness. The femoral heads when assessed as a whole were quantitatively equal. Segmental defects in perfusion were not observed.

EXPERIMENT II: (Table III)

1. In 30 immature rabbits the left hip was dislocated and left unreduced. Groups of 5 animals each were infused and sacrificed at 10 minutes and at 1, 2, 3, 5 and 7 days after dislocation.
Figure 20 illustrates the microangiographic findings at 10 minutes. Disturbance of perfusion was present and significant in all cases. The perfusion deficit varied, with a gradual transition from reduced to absent dye in the antero-medial part of the femoral head. The extraosseous vessels were obscured by dye which had leaked from damaged vessels below and behind the femoral head.

At 24 hours after dislocation, a greater circulatory disturbance was observed (Figure 20). Constant filling was seen postero-laterally, but the antero-medial 1/3 to 2/3 of the femoral head was empty in all cases. Blood vessels were seen connecting the epiphysis with the posterior trochanteric notch in 4 cases, and with the greater trochanter in 3 cases, such vessels are respectively uncommon, and rare in normal immature rabbits. The extraosseous, postero-inferior vessels to and from the epiphysis did not fill.

The microangiographic picture at 2 and 3 days following dislocation did not significantly differ from that seen at 24 hours, but a fine network of extraosseous vessels was seen developing on the postero-inferior femoral neck by the third day.

Intraepiphyseal revascularization seemed to have commenced possibly on the fifth and certainly on the seventh day (Figure 21). The extraosseous meshwork of vessels noted four days earlier had enlarged and was using the postero-inferior nutrient foramen of the epiphysis in 4 cases. Perforation of the growth plate, and epiphyseal-metaphyseal anastomoses
Figure 20: The results of unreduced dislocation in immature rabbits (a) at 10 minutes and (b) at 24 hours after dislocation.
Figure 21: The microangiographic pattern 7 days following unreduced dislocation in immature rabbits.
were noted in one case each at 5 and 7 days after dislocation.

2. In 25 immature rabbits the left hip was dislocated and immediately reduced. Groups of 5 animals each were infused and sacrificed at 10 minutes, and at 1, 3, 5 and 7 days after reduction (Table III).

A profound perfusion deficit was observed in all cases within 10 minutes of reduction and this contrasted markedly with the picture at 10 minutes following unreduced dislocation (Figure 22). Unlike these unreduced however, the circulatory disturbance did not increase within 24 hours, but rather compared well with the microangiographic picture seen at 7 days following unreduced dislocation (Figure 23). Early reduction seemed to enhance early recovery, and this was almost complete at 5 and 7 days after reduction (Figure 24).

A notable feature in those animals reduced early, was early use of the postero-inferior nutrient os to the epiphysis, as a route of blood supply. This was observed on the third day. Furthermore, filling of the epiphyseal end of the principal epiphyseal vessels was observed in three cases on the seventh day, although they did not obviously connect with the main capsular vessels.

3. The remaining subgroups in this experiment were reduced at 24 and at 48 hours, so accounting for 40 immature animals (Table III).

In terms of the rate and extent of recovery of dye perfusion to the femoral head, those reduced at 24 hours did not differ from those reduced later. More important,
Figure 22: The microangiographic pattern in immature animals (a) at 10 minutes after immediate reduction and (b) 10 minutes after unreduced dislocation.
Figure 23: Microangiographic pattern in immature animals (a) 24 hours after immediate reduction and (b) 7 days after unreduced dislocation.
Figure 24: Microangiographic pattern in immature animals (a) at 5 days and (b) 7 days following immediate reduction.
neither subgroup was seen to be significantly distinct from those left unreduced. Furthermore, recovery seemed to date not from the time of dislocation, but rather the time of the last injury to the joint, that is, reduction.

EXPERIMENT III:
1. In 10 mature rabbits the left hip was dislocated and unreduced. Groups of 5 animals each were infused and sacrificed at 10 minutes and 7 days (Table IV).

   At 10 minutes after dislocation circulatory disturbance was observed in 4 out of 5 cases but in one only was this disturbance more than slight.

   At 7 days all animals but one had perfusion equal or greater than control. One had a segmental absence of vessel filling postero-medially (Figure 25).

2. In 10 rabbits the left hip was dislocated. 5 were reduced immediately and 5 at 24 hours. All were sacrificed 7 days after reduction (Table IV).

   Based on the microangiographic findings, these reduced subgroups could not be told apart, nor indeed did they significantly differ from those left unreduced.

   The intraosseous epiphyseal-metaphyseal anastomoses across the epiphyseal scar filled in all cases, and seemed responsible as an avenue of blood supply and drainage in adult animals.
Figure 25: Microangiographic pattern in mature rabbits (a) at 10 minutes and (b) 7 days after unreduced dislocation.
EXPERIMENT IV:

In 5 mature and 5 immature rabbits the left hip was dislocated and reduced at 12 hours. All were sacrificed 7 days later (Table V)

1. Mature: As expected from Experiment III (results of which were not available at the time), reduction at 12 hours resulted in microangiographic findings indistinguishable from those adult animals unreduced, or reduced late.

2. Immature: The findings in this subgroup similarly did not differ from those in animals unreduced, or reduced late, in Experiment II.

HISTOLOGICAL FINDINGS:

Histological investigation was intended principally to augment analysis of the microangiographic findings. The aim in each case was therefore to establish the fact and extent of bone necrosis if present, and to assess the degree, and efficacy of revascularization, regeneration and repair. Changes within the cartilage of the articular surface and growth plate were not closely analysed, and no account of such alterations will appear in the text.

The hall-marks of viability were evident in all control sections. Marrow, although varying in cell content and haemopoietic activity, nevertheless retained its highly
organized character throughout. The trabeculae stained uniformly, and considerable lengths of their cancellous surfaces were seen to be covered by a layer of endosteal cells (Figure 26).

Osteocyte morphology varied with the distance of the cell from the nearest cancellous surface or Haversian system. In superficial situations the osteocyte nuclei appeared large, avoid and had a distinct chromatin network. More deeply, the nuclei became smaller, spindle shaped, darker staining, and lost the fine chromatin meshwork. Red blood cells were consistently seen within the juxta articular and juxta epiphyseal system of vessels.

Bone death was always obvious. Empty lacunae were seen over extensive areas, alone, or in conjunction with lacunae containing the remains of osteocytes such as poorly stained debris, faintly outlined anuclear cells, or pyknotic nuclei. Such bone always contrasted markedly with the control side, and was accompanied by circumstantial evidence of death, ranging from total and wide-spread marrow infarction with scattered debris and ghost cells, to granulation tissue replacement of marrow with hyperactive new bone apposition (Figure 27). Between these two extremes a wide range of fibrocellularity of the marrow and endosteal activity was observed.

New bone was easily recognized. Always it was marked off from the dead bone by a distinct cement line which
Figure 26: Histological section (H & E) of the normal femoral head. The marrow presents an organized appearance and is haemopoietically active. The lacunae contain viable osteocytes. An endosteal layer of osteoblasts covers the center trabeculum.

Figure 27: Histological section of the left femoral head following prolonged unreduced dislocation. There are scattered areas of empty lacunae, and lacunae containing poorly staining debris. There is hyperactive new bone formation which has spread to and partly replaced the marrow cavity.
sheared easily during processing. It was common therefore to find new bone partly or completely separated from the underlying dead trabeculae and appearing as a halo of bone within the cancellous spaces. The deeper layers of new bone were usually basophilic and woven in type, and the superficial layers lamellated. The osteocytes were more numerous and closely packed than in the older bone and had large ovoid nuclei and well outlined chromatin.

Endosteal activity was however variable. Some cancellous areas were clearly delineated from surrounding dead bone by virtue of their fibrous content. These spaces contained closely packed fibrous tissue, of poor cellularity, intimately associated with the dead trabeculae, but without an intervening layer of endosteal osteoblasts (Figure 28). Suprisingly, avascularity was not a feature in these cases (Figure 29) and the reason for this apparent dormancy was not clear. More commonly however whole areas of dead trabeculae were outlined by many layers of osteoblasts rapidly laying down reactive Bone (Figure 27). This new bone increased at the expense of the cancellous spaces, and seemed to increase the total bone mass. This phenomenon was commonly observed to spread to the cancellous spaces per se, where large groups of osteoblasts were found in mosaic form, laying down bone de novo (Figure 27).
Figure 28: Histological section of the left femoral head following dislocation. The marrow is replaced by granulation tissue throughout. The trabeculae contain empty lacunae and basophilic new bone apposition is seen to the left of the section. The new bone is separated from the underlying dead trabeculae by a distinct cement line. There is no endosteal activity to the right of the section.

Figure 29: High power photomicrograph from dislocated left femoral head. The lacunae are empty and the marrow replaced by fibrous tissue. Despite the close proximity of the blood vessels, there is no endosteal layer of cells or osteoblastic activity.
Figure 30: Analysis of the Histological Findings.
A. Superior aspect of the left femoral head and neck
B. The sampling locations for histological sections
C. Light-microscopic analysis. The solid shading, as an example, represents avascular necrosis.
D, E and F: Illustration of how the histological features may be transferred to a composite map of the femoral head, and so indicate the location and extent of avascular necrosis.
As illustrated in Figure 30, a composite map of the location and extent of histological viability, death, revascularization and repair could be made in each case, based on the serial sections of the femoral head.

Total or sub-total necrosis was the most common finding overall (70%). Complete viability or minimal bone death (limited to one or two medial trabeculae) occurred in 24% of all cases examined. It therefore seemed the histological features almost obeyed an "all or none" law. The findings will consequently be presented in terms of these two extremes. The overall effects of skeletal maturity, reduction and early reduction are outlined in Tables VIII, IX and X. The influence of skeletal maturity on the individual results of unreduced dislocation and of early and delayed reduction is of necessity based on smaller groups of animals which render the conclusions less significant. This data is presented in Table XI.

A statistical analysis of the histological findings will appear in the Discussion of this study.

C. RADIOLOGICAL FINDINGS:

This report is based on in vivo x-ray examination of the separated hind limbs of 60 long-term survival animals, after sacrifice (Table VI) The plates from 55 cases were suitable for assessment.
Abnormal radiological features were frequent and many, but highly variable, even within any one subgroup. The salient features will be summarized.

Increased radiolucency of the femoral neck was the most common observation. This finding rendered accurate assessment of the injured femoral head radiodensity difficult and frequently erroneous. For this reason the right and left femoral heads were compared only after blacking out the remainder of the upper femora with dark paper.

In the majority of animals the right and left femoral heads were indistinguishable in terms of the radiodensity alone. Absolute increase in density (Figure 31), was most common in those reduced (9 of 39 cases) and absolute decrease (Figure 32) in those unreduced (6 of 16 cases). The femoral neck appeared osteopaenic in the majority of injured hips. Occasionally this radiolucency presented a moth-eaten cystic appearance with surrounding sclerosis. Coxa vara was evident in more than 50% of the immature animals regardless of reduction, but was most severe in those unreduced and in this subgroup commonly associated with deformity of the femoral head per se. Deformity of the femoral head was not observed in those reduced and coxa vara in these animals was accounted for by shortening and widening of the femoral neck, and in some subcapital erosion of the infero-medial part of the femoral neck.
The appearance of the growth plate varied from widening, which was rare, to premature closure which was most common and advanced in those unreduced.

Generally speaking the reduced subgroups could not be told apart on the x-ray findings, and those unreduced were distinct only by virtue of the degree to which they demonstrated the various abnormal radiological features.

COMPARATIVE HISTOLOGY AND RADIOLOGY:

The findings may be simply stated. Increased radiolucency was always associated with histological evidence of unbalanced resorption of bone within the epiphysis. This was most common in those unreduced, and frequently associated with epiphyseal hyperaemia. Increased radiodensity was always associated with avascular necrosis and new bone apposition to the dead trabeculae. However, radiodensity judged comparable with the control side was compatible with both living bone, and necrotic bone with new bone formation.
Figure 31: In vitro radiograph of the right and left proximal femora from an adult rabbit eight weeks following dislocation, and reduction at 24 hours. Note the absolute increase in radiodensity of the left femoral head (to the right of the illustration).
Figure 32: In vitro radiograph of the proximal femora from an adult rabbit with long term unreduced dislocation of the left hip. Note the diminished radiodensity of the femoral head and superior femoral neck, and associated coxa vara, of the left hip. (toward the right of the illustration).
DISCUSSION

Death of the femoral head, in whole or part, may be expected to ensue in 10% of children and up to 30% of adults following traumatic dislocation of the hip. The age in childhood, skeletal maturity, severity of the injury, and duration of dislocation considerably influence the incidence of avascular necrosis but the individual contribution of these factors to the outcome is difficult to assess as they are closely inter-related.

The cause of avascular necrosis of the femoral head after dislocation is not known, but we have good reason to believe that damage to the intracapsular or immediately extracapsular course of the epiphyseal vessels is a major factor in its genesis. The series of events that occur following displacement, and how they affect the circulation within the femoral head is similarly unknown. Our current concepts in this regard are based largely on indirect evidence from clinical, pathological, radiological and experimental data. SEVITT investigated one case of posterior dislocation of the hip in an eighteen year old male, by microarteriography. The femoral head had been reduced soon after injury, but the patient later succumbed to associated injuries. Diaphyseal-metaphyseal connections were demonstrated within the base of the femoral neck, but the femoral head was
largely avascular, and the retinacular vessels failed to fill. This is the only report of its type in the literature.

Experimental dislocation of the hip in animals similarly causes avascular necrosis of the femoral head. The incidence and extent is however highly variable between individual investigators. BOHR using microarteriography, documented the weekly series of events following manual dislocation of the hip in newborn rabbits, but we are aware that femoral head viability is particularly dependant on the ligamentum teres vessels at this age in rabbits. The affects of this injury on adult and growing animals have not been sufficiently compared in any single study. The influence of reduction has not been investigated.

The rabbit is a suitable experimental model. Anatomical dissection, microarteriography and the results of selective interference with the postero-inferior nutrient vessels of the capital epiphysis has proven the functional similarity between these vessels and the superior retinacular system in man. The individual role of the ligamentum teres vessels is uncertain in each species. These vessels are perhaps most important as a route of revascularization should the femoral head suffer necrosis. Species differences in this regard would be minimized by dislocation which of its nature implies ligamentum teres rupture.
The value of microangiography in terms of its functional relationship to the actual perfusion by blood of the femoral head, is difficult to assess. The dye used was designed during extensive pilot studies to fill both the afferent and efferent vessels, and so cross the capillary bed. For this reason the larger intraosseous vessels were usually obscured and perfusion assessed by the location and extent of microvascular filling. The viscosity of the dye compared with whole rabbit blood at body temperature was 1.6. The aggregate size of the carbon particles as measured in vitro did not exceed 4 microns, and on repeated examination of bone sections prepared for routine histology and by the Spalteholz technique, extravasation of dye from the vessels was not observed (Figures 7 and 33). The yield of technically acceptable results within the control hips was high. Furthermore the pattern of segmental circulatory disturbance, as illustrated, was usually consistent, and reflected a gradual transition from case to case. For these reasons I believe that the microangiographic pattern observed bore a close relationship to the patency of the microvasculature, and so the perfusion by blood of the femoral head, at the time of infusion.

The severity of the injury was standardized by one operator using one technique throughout. This has limitations which are realized, but offers considerably more control over the trauma than seen in the comparable clinical situation in man where the mechanism and severity of the injury cannot be considered alike in any two cases.
Figure 35.: Histological sections of the femoral head following infusion. The dye is clearly outlined and well contained within (a) the marrow sinusoids and (b) the capillaries.
The animals were grouped according to skeletal maturity and subgrouped on the basis of the duration of dislocation and the time of reduction. I therefore believe that valid and valuable conclusions may be drawn with regard to the individual influence of these factors on the outcome.

Reduction was usually clinically obvious. Nevertheless it was confirmed in all cases by fluoroscopic examination of the hip within ten minutes. Repeat fluoroscopy at seven days and monthly x-rays served as further confirmation in those animals survived past seven days. Clinical examination (leg-length) under anaesthesia at the time of infusion and the position of the femoral head after careful dissection was used to rule out spontaneous redislocation when the animal was sacrificed within seven days. Daily fluoroscopic examination would have been 'ideal, and close to the council of perfection. The need for a general anaesthetic in each case and at each examination however rendered this an impractical goal.

In this study, dislocation caused a significant perfusion deficit within ten minutes in immature animals. The disturbance was segmental in type and seemed constant in character insofar as the antero-medial part of the femoral head consistently suffered diminution in vascular
filing (Figure 20(a)). Judging by the findings, in animals sacrificed after ten minutes, the circulatory disturbance worsened within twenty-four hours and thereafter remained constant in degree and extent until five to seven days after injury, when recovery commenced. (Figure 20(b) & 21) Such recovery has been observed to occur in rabbits and other animals, but usually within the second week after injury. These investigators had however induced massive epiphyseal necrosis by selective or gross interference with the epiphyseal-metaphyseal vessels. ROSINGH has observed revascularization to occur with the infarcted rabbit capital epiphysis three days following injury. In this study the principal extraosseous epiphyseal vessels failed to fill up to and including seven days from dislocation. Epiphyseal vascular connections with the greater trochanter and posterior trochanteric notch were observed to enlarge and maintain perfusion of a limited part of the posterolateral epiphysis throughout. Effective recovery was coincident with appearance of a rich extraosseous network of vessels at the postero-inferior aspect of the femoral neck. This meshwork was first noticed on the third day after injury, and seemed to use the postero-inferior nutrient foramen of the femoral head as a route of supply and drainage at the seventh day. Intraosseous epiphyseometafhyseal connections were developed in one animal each at five and seven days by perforation of the growth plate.
This phenomenon was a constant feature in all of BOHR's immature rabbits, during the second week. In mature animals dislocation again caused interference with perfusion within ten minutes (Figure 25(a)). This was judged significant in one animal only. Similarly, seven days after injury only one animal demonstrated a significant circulatory disturbance within the femoral head (Figure 25(b)). Filling of the intraosseous epiphyseometaphyseal anastomoses across the epiphyseal scar was noted in all mature animals at both periods. The major extraosseous epiphyseal vessels as in growing animals, failed to fill at ten minutes and seven days.

Immediate reduction in growing rabbits was associated with a most profound perfusion deficit at ten minutes (Figure 22) indicating greater injury than that induced by dislocation alone. However judging by the microangiographic findings at 1, 3, 5 and 7 days, early reduction had obviously enhanced early and complete recovery (Figure 24). Again it was noted that recovery paralleled use of the postero-inferior route of supply to the femoral head, and in some cases use of the major postero-inferior retinacular vessels. These vessels did not obviously connect with the capsular stem vessels however and presumably filled by a more circuitous route, either via the "circulus articuli vasculosus" or in a retrograde fashion from the metaphysis.
Recovery of the femoral head perfusion in immature animals reduced at 12, 24 and 48 hours proceeded at a rate comparable to that observed in unreduced animals. The events within the extraosseous system of vessels were also similar. It is interesting to note that revascularization seemed to date from the last manipulation of the hip. As an example, the microangiographic picture in those animals reduced at 48 hours did not compare well till 7 days after reduction, with those animals unreduced for 7 days, even though in the former the infusion was in effect conducted 9 days after the initial injury.

In adult animals the reduced and unreduced subgroups were indistinguishable on the basis of the microangiographic picture at seven days alone. Dislocation per se infrequently caused a significant perfusion deficit and so the beneficial effects of reduction, if any, were obscured.

Perfusion deficit was therefore most obvious in immature animals, increased with time and recovered with parallel recovery of an extraosseous route of blood supply. Reduction was of benefit to immature animals only and altered the expected serial events following dislocation only if achieved in less than twelve hours. Early reduction was equally beneficial, to intraosseous and immediately extraosseous circulation alike and recovery in these locations was coincident.
The principal retinacular vessels recovered only in some of those immature animals reduced early and did not obviously connect with the capsular vessels. These findings would suggest that damage to the postero-inferior branch of the medial circumflex femoral artery before or during its passage through the hip joint capsule was to a large part responsible for the circulatory disturbance induced by dislocation. This was confirmed at gross dissection by the frequent finding of a torn or avulsed inferior joint capsule, presumably suffered during postero-superior excursion of the femoral head and neck. Early reduction offset whatever detrimental effects continued displacement caused. It is well to remember that all rabbits reduced late were allowed unlimited activity until the time of reduction. It is reasonable to presume such activity added insult to injury.

The intraosseous epiphyseo-metaphyseal anastomoses minimized the effects of dislocation in adult animals and recovery was not dependant on a parallel return of an extraosseous route of blood supply to the femoral epiphysis. The influence of early reduction, if any, was therefore masked.

The histological characteristics of revascularization and repair following avascular necrosis of the femoral head or other osseous tissue has been well and repeatedly described in man \(^3,13,23,25,26,56,85,98,99,101\) and animals \(^10,11,12,15,47,94,95,122,138\). Granulation tissue originating
101.

principally from the metaphysis and fovea centralis (if
the ligamentum teres is intact) invades the infarcted
cancellous spaces and is followed by an advancing wave
of new bone which is laid down upon the non-viable
trabeculae. Transformation of the cellular elements of the
invading vascular connective tissue, to osteoblasts,
is responsible for this new bone. This process was
termed "creeping substitution" by PHEMISTER\textsuperscript{85,86,87} although
later BABECHKO and HARRIS\textsuperscript{10} were to describe it as "creeping
apposition" and so stress the initial tendency towards
bone formation, rather than coexisting regeneration and
resorption. The delay in man between invasion and cellular
transformation is variable and depends on the age, site
and functional use of the part.\textsuperscript{86,87} In the rabbit this
duration is less variable. Complete reossification of the
infarcted capital epiphysis has been demonstrated by six
weeks in immature rabbits following experimental epiphyseal
separation,\textsuperscript{47} and by eight weeks in adult rabbits after
subcapital osteotomy.\textsuperscript{10} Reossification in the rabbit is
therefore dependant on the rate of revascularization and
the speed and extent of revascularization depends on the
hindrances met en route. The growth plate can offer such
a hindrance and has been demonstrated to act as a staunch
barrier to vascular invasion from the metaphysis in
experimental animals.\textsuperscript{10,47}
ROSINGH and his associates have described four phases in the vascularization and repair of the avascular capital epiphysis in the rabbit. The first phase is characterized by tissue decay, the second by granulation tissue invasion, the third by cellular differentiation within the new connective tissue and new bone apposition, and the fourth or reparative phase, by gradual return of the marrow elements to normal. These authors had noticed revascularization within three days of injury in some cases. A similar series of events was observed by BRASHEAR following experimental infarction of the lower femoral epiphysis in the rat. In ROSINGH's study dead trabeculae were noted to remain within the apposed new bone covering for the length of the experiment, which was 21 weeks.

It was not therefore elected to repeat these studies and evaluate the histological series of events following dislocation in this study. It was presumed that repair would follow revascularization, and that the earlier microangiographic study would offer sufficient information regarding the rate and extent of blood vessel invasion. It was further presumed that avascular bone if observed up to 10 weeks following injury would have dated from the time of dislocation or reduction. Separate analysis of animals sacrificed at four and at eight weeks after dislocation did not reveal any evidence of continued bone damage.
In this study total or subtotal avascular necrosis occurred in 51% of adult and 84% of growing animals. Absent or minimal necrosis occurred in 37% of mature and 14% of immature animals (Table VIII). These differences are statistically significant (Total or subtotal: p value less than 0.05. Minimal of absent: p value equals 0.05). The histological and microangiographic findings were therefore complimentary and favored the adult animal. However the overall incidence of 31% extensive necrosis in mature animals was unexpected, and surprising in view of the microangiographic findings at 10 minutes and 7 days after dislocation (Figure 25). There are perhaps two explanations. One, as suggested by STEWART and MILFORD that intra cellular damage caused by the force and counterforce of the injury largely governed the outcome regardless of the vascular injury and repair. This would not explain the small, but significant difference between adult and growing animals. The literature in general and this study cannot support or refute this hypothesis. Alternatively the adult femoral heads may have suffered periods of prolonged hypoxia not stressed by the outline of the study. As suggested by WOODHOUSE and demonstrated by ROSINGH and JAMES using Fuelgen-DNA microdensitometry, osteocytes suffer irreparable cellular damage after six hours of anoxia. Perfusion of the femoral head was demonstrated to considerably deteriorate within 24 hours of dislocation in immature animals. (Figure 20).
This was not investigated in adult rabbits as the 10 minute and 7 day perfusion pattern and constant epiphyseometaEP metaphyseal anastomotic filling suggested limited circulatory embarrassment and early complete recovery. In retrospect, and particularly in view of the histological findings, it seems likely that 50% of adult animals suffered deterioration after ten minutes, and a prolonged period of anoxia or hypoxia of the femoral head.

Reduction overall, and particularly immediate reduction in immature animals seemed to benefit the histological outcome beneficially (Tables IX,X & XI). However, the number of animals in these subgroups is not sufficient to support this observation statistically. Nevertheless the histological and microangiographic findings are not contradictory in this regard. In adult animals reduction, even early, was not demonstrated to influence the outcome. In growing animals although early reduction enhanced early and complete recovery, profound circulatory embarrassment was demonstrated within 10 minutes (Figure 22) and only two of the four animals infused at 24 hours demonstrated recovery (Figure 23). In both mature and immature animals therefore a prolonged period of hypoxia within the femoral head during the first 24 hours, cannot be outruled by this study.
More important, the histological findings seriously challenge the influence of continued dislocation and delayed reduction on the incidence of avascular necrosis. Although in many instances in man the severity of the injury and the duration of dislocation are inter-related, BRAV's figures signify clearly that delay in reduction past 12 hours is associated with a 3-fold increase in the incidence of avascular necrosis regardless of the presence and degree of bone damage. How may these figures be interpreted? BRAV graded avascular necrosis according to the radiological features. Slight to moderate alteration in radiodensity only, without accompanying deformity of the femoral head was present in 45% of his cases. BOYD and GLASS and POWELL have stressed the difficulty and unreliability of differentiating between degenerative arthritis and avascular necrosis of the femoral head after trauma to the hip, in the absence of flattening or collapse of the weight-bearing area. Only 55% of BRAV's cases demonstrated this sign.

Does radiological examination yield an accurate index of the incidence of avascular necrosis of the femoral head after injury? BOHR and HULT have demonstrated that dead trabeculae retain normal mineralization up to five years following injury. CATTO described 12 cases of late segmental collapse following femoral neck fracture, in which the radiological features were normal until the onset of deformity. This was despite the fact that total or
subtotal necrosis of the femoral head was demonstrated on subsequent histological examination. It would seem therefore that dead bone per se has a normal radiological appearance; and that the consequences, rather than the fact of avascular necrosis are responsible for the indices on which we make a radiological diagnosis.

Revascularization and new bone apposition with increase in trabecular width and total bone content of the femoral head has been demonstrated to cause increased radiodensity in man and animals. Furthermore, collapse occurs within a segment of the femoral head which has failed to revascularize. These signs are respectively a consequence of adequate and inadequate repair and do not necessarily relate to the actual incidence of avascular necrosis. SEVITT examined 25 femoral heads removed from cadavers up to 10 years following femoral neck fracture. He found histological evidence of significant bone death in 84%, and of total or subtotal necrosis in 64%. His figures contrast markedly with the 15 to 45% incidence of avascular necrosis which has been documented on the basis of clinico-radiological criteria alone. It seems therefore that not all cases go on to develop the radiologically obvious signs of successful or hindered repair on which the diagnosis is dependant. On this basis BRAV's figures may be interpreted in a new light. Accepting that flattening or collapse of the femoral head is the most
reliable radiological index of past ischaemic necrosis, it would seem that delay in reduction past 12 hours is associated with a three-fold increase in the occurrence of frustrated revascularization and repair, but that we do not know the incidence of avascular necrosis per se.

In this study early reduction was observed to enhance early revascularization in immature rabbits. This would support the neo interpretation of BRAV's figures as discussed above.

Why then did histological examination not reveal a higher incidence of poorly vascularized segments within the femoral head in rabbits unreduced or reduced late? The important size-difference between the femoral heads of man and the rabbit must be considered in this regard. GALLIE suggested there was a physiological limit to which bone as a tissue could be expected to revascularize after ischaemic necrosis. He stated that the femoral head in small experimental animals probably fell well within this limit. Consequently factors hindering or exhausting repair in man would not be as easily demonstrated in animals.

BOYD also drew on this hypothesis of the "physiological limit" to explain the phenomenon of delayed segmental collapse in man. If we therefore accept that repair and not necrosis is influenced by the duration of dislocation, then the results of this study support the concept that early reduction will reduce the incidence of late segmental collapse.
In this study, extensive avascular necrosis was clearly more common in growing animals, chiefly on account of the growth-plate which prohibited early intraosseous collateral compensation after damage to the extraosseous epiphyseal vessels. In man, the more precarious blood supply of the femoral head before skeletal maturity is well established. It is clear that the severity of the injury which is usually greater in adults is responsible for the higher incidence of avascular necrosis after skeletal maturity. But in considering simple dislocation alone, the incidence in adults approaches, but is not less, than that seen in childhood. The reason for this discrepancy between what is expected and what is observed is not clear, but the concept of the "physiological limit" of bone repair as forwarded by GALLIE and BOYD could well be cited in explanation. This study and our current knowledge of the peculiar vascular anatomy of the femoral head would suggest that children suffer a higher incidence of ischaemic necrosis than adults following an injury of similar severity. However as the efficacy of biological repair is inversely related to the age of the organism, the child is less apt to develop the features of frustrated revascularization on which our clinico-radiological diagnosis of avascular necrosis must rest.
Absolute alteration in the radiodensity of the injured femoral head was absent or uncertain in the majority of animals x-rayed by the in vitro technique between five and ten weeks after injury. When present however the radiographic abnormality closely correlated with the histological findings. Increased radiodensity was always associated with bone death, new bone apposition, and increased bone mass within the femoral head. This has been previously reported in man and experimental animals. In particular BOHR, on examination of 20 human femoral heads removed 5 days to 5 years after femoral neck fracture found that radio-sclerosis directly and consistently related to increased trabecular width due to new bone apposition. Densitometry revealed comparable mineralization between dead and living bone. HULTH similarly concluded with x-ray diffraction that dead bone retained its normal mineralization. ROSINGH objectively estimated the bone-marrow ratio in 30 young rabbits, including 15 controls, after inducing epiphyseal necrosis. Increase in this ratio was noted 3 weeks after avascular necrosis and coincided with new bone formation and increased radiodensity. The ratio returned to normal from 6 weeks onwards with concurrent reduction in radiodensity.
When present therefore, increased radiodensity of the femoral head always signified avascular necrosis. In the majority of cases however, the avascular femoral head had an appearance comparable with the control side and so radiographic examination at 5 to 10 weeks did not prove a reliable index of the incidence of ischaemic necrosis.
SUMMARY

A microangiographic, histological and radiographic investigation of the femoral head following experimental dislocation of the hip in 220 rabbits is reported.

Dislocation of the left hip was induced manually under anaesthesia by a dorsally applied force with the hip held adducted internally rotated and slightly extended. Reduction was effected by ventral traction with the hip held in the same position.

The animals were grouped according to skeletal maturity, and subgrouped on the basis of the duration of dislocation and time of reduction. The left hip was manipulated by one operator using one technique throughout. The right hip was untouched and used as a control.

The effects of dislocation, persistent dislocation, and reduction at varying intervals (immediately, 12, 24 and 48 hours after dislocation) were studied by microangiography at 10 minutes, 1, 3, 5 and 7 days after injury, and by histological and radiographic examination up to 10 weeks after dislocation.

The purpose of the study was:

1. To establish the segmental changes in blood supply of the femoral head following experimental traumatic dislocation of the hip in rabbits.
2. To evaluate the influence of the duration of dislocation.
3. To evaluate the influence of skeletal maturity.
4. To evaluate the influence of reduction
5. To analyze what relationship the early changes in blood supply of the femoral head may bear to the later histological and radiographic findings.
CONCLUSIONS

1. Traumatic dislocation of the hip causes circulatory embarrassment in the femoral head in mature and immature rabbits. Damage to the extraosseous epiphyseal-metaphyseal vessels of blood supply and drainage is a major causative factor.

2. The perfusion deficit is most severe in immature animals, and is maximal in the antero-medial portion of the femoral head which is devoid of perfusion or considerably underperfused within ten minutes of dislocation.

3. Disturbance of circulation in immature animals worsens with continued dislocation to reach a maximum within 24 hours. Recovery does not commence until 7 days after dislocation.

4. Recovery of perfusion within the femoral head of immature animals with unreduced dislocation is coincident with development of an extraosseous network of epiphyseal blood supply and drainage on the postero-inferior femoral neck.
5. Reduction is per se injurious to the blood supply of the femoral head, but if early, enhances early and complete recovery of blood supply.

6. Reduction delayed to 12 hours or longer after dislocation does not benefit the rate and extent of return of perfusion of the femoral head.

7. In mature animals, the intraosseous epiphyseal-metaphyseal anastomoses across the obliterated growth-plate are seen to minimize the perfusion deficit induced by dislocation and enhance early and complete recovery of blood supply of the femoral head. Consequently the possible benefits of reduction are obscured.

8. Histologically demonstrable avascular necrosis of the femoral head occurs in the majority of animals regardless of skeletal maturity or reduction. It is more common and more extensive in immature animals.

9. Early recovery of blood supply does not consistently minimize or prevent histological avascular necrosis of the femoral head.
10. Abnormal radiological features within the femoral head are infrequently observed up to ten weeks after dislocation, but correlate well with the histological findings when present.

11. Absence of abnormal radiological features within the femoral head does not rule out avascular necrosis.
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<thead>
<tr>
<th>AUTHOR</th>
<th>OUTCOME</th>
<th>GRADE</th>
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</thead>
<tbody>
<tr>
<td>Thompson &amp; Epstein</td>
<td>Excellent or Good</td>
<td>I: 66%</td>
</tr>
<tr>
<td></td>
<td>Fair or Poor</td>
<td></td>
</tr>
<tr>
<td>Stewart &amp; Milford</td>
<td>Excellent or Good</td>
<td>I: 66%</td>
</tr>
<tr>
<td></td>
<td>Fair or Poor</td>
<td></td>
</tr>
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</table>

* Amended Grading (by the author)

I: simple dislocation
II: dislocation & associated acetabular rim fracture. One or more large fragments.
III: dislocation & greater associated bone damage
TABLE II

EXPERIMENT I

Normal Rabbits

MATURE - 5 animals

IMMATURE - 5 animals

R = L
### TABLE III

#### EXPERIMENT II

<table>
<thead>
<tr>
<th>Subgroup</th>
<th>Number</th>
<th>5 animals sacrificed</th>
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<tr>
<td>Dislocated alone</td>
<td>20</td>
<td>@ 1,3,5 &amp; 7 days</td>
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<tr>
<td>Reduced - immediate</td>
<td>20</td>
<td>@ 1,3,5 &amp; 7 days</td>
</tr>
<tr>
<td>Reduced - @ 24 hours</td>
<td>20</td>
<td>@ 1,3,5 &amp; 7 days</td>
</tr>
<tr>
<td>Reduced - @ 48 hours</td>
<td>20</td>
<td>@ 1,3,5 &amp; 7 days</td>
</tr>
<tr>
<td>Dislocated alone</td>
<td>5</td>
<td>@ 10 mins</td>
</tr>
<tr>
<td>Reduced - immediate</td>
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<td>@ 10 mins</td>
</tr>
<tr>
<td>Dislocated alone</td>
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<td>@ 2 days</td>
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### TABLE IV

**EXPERIMENT III**

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<th>Subgroup</th>
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<tr>
<td>Dislocated alone</td>
<td>5</td>
<td>@ 7 days</td>
</tr>
<tr>
<td>Reduced - immediate</td>
<td>5</td>
<td>@ 7 days</td>
</tr>
<tr>
<td>Reduced - @ 24 hours</td>
<td>5</td>
<td>@ 7 days</td>
</tr>
<tr>
<td>Subgroup</td>
<td>Number</td>
<td>Sacrificed</td>
</tr>
<tr>
<td>-----------------------</td>
<td>--------</td>
<td>------------</td>
</tr>
<tr>
<td>MATURE: Reduced @ 12 hrs</td>
<td>5</td>
<td>@ 7 days</td>
</tr>
<tr>
<td>IMMATURE: Reduced @ 12 hrs</td>
<td>5</td>
<td>@ 7 days</td>
</tr>
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### Table VI

**Long Term Animals for Histo logical Examination**

<table>
<thead>
<tr>
<th></th>
<th>Immature - 35 animals</th>
<th>Number</th>
<th>Average Duration</th>
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<tbody>
<tr>
<td>Dislocated</td>
<td></td>
<td>9</td>
<td>7 weeks</td>
</tr>
<tr>
<td>Reduced - immediate</td>
<td></td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>Reduced - @ 24 hours</td>
<td></td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>Reduced - @ 48 hours</td>
<td></td>
<td>10</td>
<td>5</td>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>Mature - 25 animals</th>
<th>Number</th>
<th>Average Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dislocated</td>
<td></td>
<td>8</td>
<td>10 weeks</td>
</tr>
<tr>
<td>Reduced - immediate</td>
<td></td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>Reduced - @ 24 hours</td>
<td></td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Reduced - @ 48 hours</td>
<td></td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Number</td>
<td>Average Duration</td>
<td></td>
</tr>
<tr>
<td>----------------</td>
<td>--------</td>
<td>------------------</td>
<td></td>
</tr>
<tr>
<td>IMMATURE - 15 animals</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Dislocated</td>
<td>5</td>
<td>4 weeks</td>
<td></td>
</tr>
<tr>
<td>Reduced - immediate</td>
<td>5</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Reduced - delayed</td>
<td>5</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>MATURE - 10 animals</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dislocated</td>
<td>5</td>
<td>3 weeks</td>
<td></td>
</tr>
<tr>
<td>Reduced - immediate</td>
<td>5</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>
TABLE VIII

THE EFFECT OF SKELETAL MATURITY AT THE TIME OF INJURY, ON THE HISTOLOGICAL OUTCOME, REGARDLESS OF REDUCTION

**MATURE:** 35 Rabbits

- Total or subtotal necrosis - 18 animals (51%)
- Minimal or absent necrosis - 13 animals (37%)

**IMMATURE:** 50 Rabbits

- Total or subtotal necrosis - 42 animals (84%)
- Minimal or absent necrosis - 7 animals (14%)
TABLE IX

THE INFLUENCE OF REDUCTION, ON THE HISTOLOGICAL OUTCOME, REGARDLESS OF SKELETAL MATURITY

<table>
<thead>
<tr>
<th></th>
<th>Unreduced: 27 Rabbits</th>
<th>Reduced, early or delayed: 58 Rabbits</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Total or subtotal necrosis</td>
<td>- 21 animals (78%)</td>
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TABLE X

THE INFLUENCE OF EARLY REDUCTION, ON THE HISTOLOGICAL OUTCOME, REGARDLESS OF SKELETAL MATURITY

<table>
<thead>
<tr>
<th>Condition</th>
<th>Number of Rabbits</th>
<th>Total or subtotal necrosis</th>
<th>Animals (%)</th>
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<tbody>
<tr>
<td>Immediate Reduction: 27 Rabbits</td>
<td></td>
<td>16</td>
<td>59%</td>
</tr>
<tr>
<td>Total or subtotal necrosis</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delayed Reduction: 31 Rabbits</td>
<td></td>
<td>23</td>
<td>74%</td>
</tr>
<tr>
<td>Total or subtotal necrosis</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unreduced dislocation: 27 Rabbits</td>
<td></td>
<td>21</td>
<td>78%</td>
</tr>
<tr>
<td>Total or subtotal necrosis</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### TABLE XI

**THE INFLUENCE OF BOTH SKELETAL MATURING & TREATMENT ON THE INCIDENCE OF TOTAL OR SUB-TOTAL HISTOLOGICAL AVASCULAR NECROSIS**

#### IMMATURE: 50 Rabbits
- Unreduced Dislocation: 14 animals
  - Total or Subtotal necrosis: 13 animals (94%)
- Early reduction: 14 animals
  - Total or Subtotal necrosis: 10 animals (71%)
- Delayed reduction: 22 animals
  - Total or Subtotal necrosis: 19 animals (86%)

#### MATURE: 35 Rabbits
- Unreduced dislocation: 13 animals
  - Total or subtotal necrosis: 8 animals (61.5%)
- Early reduction: 13 animals
  - Total or subtotal necrosis: 6 animals (46%)
- Delayed reduction: 9 animals
  - Total or subtotal necrosis: 4 animals (44%)
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