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OBSERVATIONS ON THE BLOOD SUPPLY OF BONE
IN THE DOG

by

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BIBLIOGRAPHIC SKETCH

The author, Allan Joseph Cawley, was born in Kingston, Jamaica, B.W.I., on February 21st, 1928.

He received his primary education in Jamaica at the Camperdown and Suthermere preparatory schools from 1933 to 1939. In 1940, he was enrolled at Jamaica College where, in 1943, he obtained the Junior School Certificate, and in 1945 the Senior School Certificate of Cambridge University, England.

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His association with the Department of Agriculture of Jamaica was re-established in June 1952, this time in the capacity of Veterinary Officer. In August 1952 he was appointed Veterinary Officer, Northern Division, a post which was held until September 1953.

In September 1953, the author emigrated to Canada to become a graduate assistant in the Small Animal Division of the Department of Medicine and Surgery of the Ontario Veterinary College. His interest
was primarily surgery, particularly the orthopaedic surgery of small animals. Promotion to the rank of lecturer was achieved in December 1953 and to assistant professor in April of 1956, at which time he became the Veterinary Radiologist of the Ontario Veterinary College.

Enrollment in the School of Graduate Studies, University of Toronto, took place in the fall of 1955. The field of study chosen was orthopaedics under the supervision of the Orthopaedic Service of the Department of Surgery of the University of Toronto.
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INTRODUCTION

The rate of healing of fractured bones is influenced by a number of factors. Some causes of delayed union can be eliminated in a patient by the use of antibiotics, adequate immobilization, debridement, etc. Perhaps the cause of delayed union which produces most concern and about which very little can be done, at this time, is impoverished blood supply. In order to qualify oneself to prognose, and perhaps to treat rationally potential cases of delayed union, it is evident that the blood supply of bone in general, and more specifically the blood supply of affected bone must be known.

In undertaking this work it was hoped that the experiments carried out would throw some light on the origins and courses of the numerous blood vessels which supply and drain bone. Knowledge of the reaction of bone under certain conditions and the basic vascular pattern of bone is applicable to all the long bones. Studies were carried out on the tibia of the dog. The choice of the tibia as the bone to be studied was made primarily because of the frequency with which delayed union is associated with the lower third of this bone in man (Henderson 1926 and Urist, Mazet and McLean 1954) and because the tibia lends itself to the technical procedures involved in this series of experiments.

The experiments were set up in an attempt to demonstrate, by injection techniques and physiological experiments, whether any specific portion of the tibia received its blood supply via the periosteal, metaphyseal, or nutrient vessels or whether any portion of the bone received its blood supply from a combination of these. It
was realised at the outset that the factors involved in determining the blood supply of bone were numerous and could not all be investigated in a work of this size. In order to arrive at some conclusions and perhaps stimulate interest in such an approach to the problem, it was decided to limit the number of animals used in each phase of the experiments. To accomplish these ends, tibias were taken from dogs up to eighteen months of age and divided into three series, 1) a control series, 2) an injection series, 3) a physiological series.

The control series consisted of tibias of normal dogs or normal tibias of dogs from the injection or physiological series. These bones were injected approximately one hour after sacrifice, a time at which it was felt that only minimal vascular spasm would occur as a deterrent to the progress of the injection medium through the vascular system. That arterial spasm could influence the degree of injection has been shown by Barnes and Trueta\(^3\) (1942) and Mustard and Simmons\(^4\) (1953).

The injection series of tibias were prepared by removal of one of the three sources of blood by ligating or severing the nutrient vessels, and stripping the periosteum and fractures of the proximal and distal ends of the tibia, in order to remove the metaphyseal source of blood supply. These animals were kept alive for three days before injection so that any thrombosis of the minute arterioles or venules resulting from the trauma of surgery likely to occur would have by this time resulted. This, it was felt, was an important step in the elimination of "false positive" injections which would have
resulted from vessels which would thrombose at a later date, and was a short enough period to prevent revascularization of the bone in spite of the interposed "teflon" envelope.

The physiological series of tibias were prepared in the same manner as the injection series, but the animals were kept alive for three weeks so that proliferative and degenerative changes of the osteoblasts and the osteocytes would be evident histologically. These specimens were also injected so that a gross examination of the vascular pattern could be carried out.

In order to determine whether the nutrient artery supplies blood to the cortex as it courses through the nutrient foramen, experiments were done in the injection series for three days and in the physiological series for three weeks. In these animals the metaphyses of the bone were removed, the periosteum stripped, and the medulla reamed and brushed out with a stiff brush, then filled with bone wax. The nutrient vessels were left intact. The converse of this experiment, nutrient vessel severence and medulla plugging in the presence of an intact periosteum and metaphyses, was done with the hope of determining the ability of the metaphyseal and periosteal vessels to maintain cortical vitality in the absence of nutrient vessels and medulla.

R - Polytetrafluoroethylene, Dupont Company of Canada, Ltd.
R - Bone Wax - Hertz and Company, Toronto.
REVIEW OF THE LITERATURE

The blood supply of bone is intimately related to the formation of callus and the healing of fractures. In fact the purpose of any study of the blood supply of bone is solely a means of establishing the probability of healing of given fractures.

That the blood supply of bone is important in osteogenesis, as well as in decalcification has been shown by Jones and Roberts and Ghomley and Stuck. The former workers produced decalcification of bone "in vivo" by feeding a calcium-poor diet and ammonium chloride to produce acidosis in dogs. This resulted in decalcification of the bones of the animal and an accompanying increase in vascularity. This increased vascularity of resorbing bone was also observed by Jaffe (1930). Fractures of such bones were found to heal more rapidly than fractures of normal bone. For the same reason cancellous bone will unite more rapidly than cortical bone, and a cancellous bone graft "takes" more rapidly and unites better than a cortical graft.

The problem of blood supply of bone has been attacked by a number of workers in various ways. Perhaps Lexer's (1904) work remains the classical work in this field. He established that the blood supply of the tibia was derived from epiphyseal, metaphyseal, nutrient, and periosteal arteries. The epiphyseal arteries entered the periphery of the epiphysis and dispersed throughout those portions of the bone only. The metaphyseal vessels entered the ends of the diaphysis, branched, and anastomosed with the medullary vessels in these regions.
The nutrient artery distributed an ascending and a descending medullary branch, which distributed branches to the longitudinally placed Haversian canals. In addition, the periosteum supplied arterial twigs which entered the cortex from the exterior.

That the periosteum is osteogenic and is the chief agent in the healing of bone defects was conclusively shown by Flourens (1842). Kolodny (1923) held a similar view. The credit is usually given to Duhamel (1742) for the first scientific approach to the problem of periosteal osteogenesis. His work, which was done in 1739, consisted of the subperiosteal implantation of silver wires. Periosteal callus covered these wires some weeks later. Duhamel's work on periosteal osteogenesis later received support from Heine (1836) and Bisgard (1935), both of whom observed regeneration of ribs following their subperiosteal removal. Contradictory results were achieved by Gallie and Robertson (1914), who performed the same experiments as Heine and Bisgard. Gallie and Robertson worked with adult dogs, unlike the other two workers. Axhausen (1907 and 1909) showed that periosteum was in fact osteogenic when he produced new bone from transplanted periosteum. This was refuted by MacEwen (1912), who apparently considered the fibrous stratum of the periosteum to be the only component of this tissue. It is now accepted that the periosteum is, without doubt, osteogenic.

That a plexus of vessels is to be found in the periosteum has not been disputed; however, the origins and terminations of these vessels have been debated. Lexer did not speculate as to where
the periosteal vessels arose, but was of the opinion that the periosteal plexus supplied the cortex of long bones. Kolodny assumed that the soft tissues surrounding the long bone were the origin of the periosteal vessels when these structures were removed in an attempt to deplete the periosteum of its blood supply. Starr (1947) was of the opinion that the periosteal plexus originated from "the fascial and muscular (arterial) twigs adjacent to the bone". Brookes and Harrison (1957) described periosteal arteries in the tibia of the rabbit. These arteries were constant and were derived from specific points on the arteries of the leg.

The presence of periosteal arteries entering cortical bone was noted by Lenger (1876), Testut (1880), Lexer (1922) and Kolodny (1923) and Lewis. Ham (1952) visualized the periosteal vessels as contributing to the Haversian system. Merneffe (1951) stated that only the outer third of the cortex of the long bones of rabbits is dependent on the periosteal blood supply. Wingate, Todd (1927), Watson-Jones and Roberts (1934) emphasized, on clinical grounds, that elevation of the periosteum without establishment of a collateral blood supply invariably resulted in the death of the underlying cortical bone. Todd and Iler (1927) suggested that fragments of cortical bone from which the periosteum had been raised at the time of fracture did not necessarily die but were reduced in vitality. These fragments did not produce new bone but were incorporated in the callus. On the other hand Moore and Corbett (1914) were of the opinion that the periosteal circulation was of no value.
in the healing of fractures. Drinker, Drinker and Lund (1922) concluded from injection experiments that the periosteal circulation was of no importance in their subsequent studies of the vascularization of the bone marrow. Johnson (1927) did not find that the periosteal vessels extended below the cortex, and he believed that they played no part in the nutrition of the spungiosa, endosteum, or marrow. Brunschwig (1930) was unable to produce infarction of the tibia in adult dogs after complete stripping of the periosteum; in fact the same experiment done by Wu and Miltner (1937) on young rabbits resulted in bone lengthening. Brookes and Harrison denied the very existence of periosteal vessels supplying the cortex of adult rabbits, but were of the opinion that the cortex was drained primarily through the periosteal venous plexus. That the periosteal veins drain the medulla and are extremely active was shown by Begg (1955) when he injected 50% diodone into the medulla and observed the contrast media in the superficial veins of the area within four to five seconds.

The significance of the nutrient artery to the vascularization of a long bone was investigated by Drinker et al, by injection experiments. They observed that injection of the nutrient artery alone produced an incomplete filling of the vessels in the lower end of the bone. However, in the intact bone with a ligated nutrient artery, injection was as complete as when the nutrient artery was injected. Kolodny observed that the presence or absence of a nutrient artery
did not alter the course of healing in two experiments when the periosteal circulation was disturbed; non-union occurred in both instances. It was Kolodny's opinion that nutrient artery destruction or ligation was only of importance in fractures where the periosteal blood vessels had been destroyed, especially when the fracture was so located that the periosteum of the fracture site depended very largely for its blood supply on the nutrient artery. "It would seem that the importance of the destruction of the intraossal vessels as etiology of non-union has been overestimated by nearly all writers, because it is evident that in the normal healing of all complete fractures there is always a destruction of the intraossal vessels". Ferguson (1933) stated that the interruption of the medullary arteries and the diversion of blood to the epiphyseal cartilages accounted for the increased growth rate observed in long bones affected by pathological conditions such as fractures, chronic infections, and tumours. Ligation or destruction of the nutrient artery could feasibly produce such a diversion of blood. Huggins and Wiege (1939) showed that rupture of the nutrient artery and vein produced ischaemia of the bone marrow, which was overcome in seventy days by the establishment of a collateral circulation.

Brookes (1957) occluded the nutrient supply to the femora of day-old rabbits by curettaging the nutrient foramen and packing it with bone chips. The observations made in this experiment were that there was an initial delay in growth of the bone for thirty days, after which growth proceeded at a rate in excess of normal, so that by the seventy-fifth day normal bone length was achieved. The femora with occluded nutrient foramina remained normal in length until the nine-
tieth day, when there was a lag in growth rate. The total shortening produced up to 150 days (maturity) was 3.7 percent. This maintenance of approximately 96 percent of the femoral growth was accomplished by the vascular supply of the epiphyses and metaphyses (metaphyseal circulation), according to Brookes, who assumed that even the young rabbit does not possess periosteal arteries supplying the cortex and contributing to the medullary circulation. These femora showed normal injection patterns, which suggests that the absence of the nutrient artery was compensated for by the remaining vascular supply to the bone and that the vessels injected were the original medullary vessels, which must obviously anastomose with the remaining blood supply. Brookes states that "in the rabbit the principal nutrient artery is not of vital importance because the medullary arterial system can rapidly accommodate itself to dependence on the metaphyseal arteries alone". The combined findings of Drinker et al. and Brookes contradict Harris' statement that the diaphyseal terminal arteries are end arteries.

Johnson (1927) found that a metaphyseal injection filled the whole bone with the exception of a slight central diaphyseal area. He concluded from his experiments that the nutrient artery was the chief supply for the whole bone and that the metaphyseal plexus was of almost equal importance. Trueta (1953) working on rabbit tibiae, showed that the prolonged interruption of the nutrient and periosteal circulation of the shaft resulted in increased bone growth. This was probably accomplished as a result of the hypertrophy of the metaphyseal vessels in the establishment of a collateral circulation; thus increased nutrition was afforded the epiphyseal lines.
MATERIALS AND METHODS

The exposure of the tibia was carried out by way of an antero-medial skin and subcutaneous incision, which extended from the proximal to the distal ends of the bone. In every instance the dorsal branch of the saphenous vessels, which course across the middle of the medial aspect of the bone, was preserved, since this supplies a large portion of the periosteal blood supply.

Each of the three sources of blood supply was removed from the bone in one or another of the experiments. The periosteal blood supply was eliminated by simple elevation of the periosteum, starting from a medial longitudinal incision. In cases where the nutrient vessels were preserved and the periosteum stripped, great care had to be exercised in stripping the M. Flexor hallucis longus from the tibia, otherwise the nutrient vessels would have been damaged. The metaphyseal blood supply was removed by cutting the bone across at the level of the tibial crest and in the lower third with a Gigli saw. The nutrient blood supply to the tibia was eliminated by severing the vessels at the time of periosteal stripping or by ligating them by way of an approach under the anterior border of the M. Tibialis anterior.

In the experiments where the metaphyseal blood supply was eliminated by a fracture at each end of the tibia, it was expedient to immobilize the fragments by some method, in order to prevent vascular damage. This was done with a modified Thomas' splint in all
instances where the periosteal blood supply was intact and with a vitallium bone plate whenever the peristeum was stripped. In cases where a bone plate was used two vitallium screws were inserted in the proximal and distal fragments and the central fragment was secured to the plate with silk ligatures placed subperiosteally (fig. 1). Even with these types of immobilization, thrombosis of the nutrient artery as a result of stretching occurred in about half of the experiments where the tibia was fractured and the nutrient artery left intact.

"Teflon" was interposed between the cortex and the periosteum and in the fracture lines between the metaphyses and diaphyses to prevent revascularization of the bone from the sources of blood supply which had been interrupted. In instances where the metaphyses and the periosteum were removed and the nutrient vessels left intact, a slit in the plastic envelope surrounding the central fragment of bone allowed entrance of the nutrient vessels into the bone. Care was always taken to ligate the ends of "Teflon" envelopes or cuffs to prevent revascularization beneath the plastic.

The choice of "Teflon" as the material to prevent revascularization was made because of its inertness when inserted in tissue, since (Harrison, 1957) it was felt that irritating materials would produce changes in the vascular calibre and possibly in the vascular pattern of the bone.

All operative procedures were carried out under aseptic conditions in order to eliminate the vascular changes which could be produced by infection. Infection was additionally controlled by the
use of penicillin and streptomycin given intramuscularly for the first three postoperative days.

The blood vessels of the tibia were flushed with a 2 1/2\% sodium citrate solution until the fluid in the femoral vein appeared clear. Injection was then done via the femoral artery with 10\% gelatin coloured with india ink\textsuperscript{R1}. This procedure was carried out approximately one hour after death, since it was felt that arterial constriction was less likely to occur at this time than immediately after death. Some specimens were injected eight hours post mortem with satisfactory results. It was felt desirable to show both the arterial and venous portions of the tibial vascular pattern, and the gelatin-india ink medium was immediately followed with latex solution - i.e., 56\% commercial latex\textsuperscript{R2} diluted 1:1 with ammonia water. The viscosity of the diluted latex does not permit its flow through the capillary portion of the vascular bed, but produces filling of arterioles which are just visible to the naked eye. This phenomenon of viscosity was shown by Judet et al. (1955)\textsuperscript{29} in their studies of the femoral neck using barium sulphate.

The pressure at which the injection was done was not at all critical. The criterion of good injection which was used was the appearance of the colour of the injection medium in the skin, toe

\textsuperscript{R1} Carter's India Ink.

\textsuperscript{R2} Latex Surge (clear) - Sterling Rubber Co., Guelph, Ontario.
nails, and foot pads of the leg injected. Judet et al. 29 insisted on knowing the pressure at which their injections were made; however, Trueta and Harrison 49 paid no attention to this factor. Injected specimens were placed in a cold room 40°F. for forty-eight to seventy-two hours before dissection.

After the removal of the required soft tissues from the bone, the specimens were preserved in 10% formaldehyde solution for twenty-four hours, then treated according to Spalteholz’s technique of demineralization, dehydration, and clearing by immersion in methyl salicylate.

An addendum has been included in this thesis wherein details of the methods used have been described for the benefit of those who may wish to repeat these experiments.
RESULTS -
(CONTROLS)

The Periosteal Blood Supply

The origins and anastomoses of the periosteal vessels of the tibia of the dog were determined on specimens injected with gelatin - india ink followed by diluted red latex. These specimens were dissected, and the vessels drawn as the dissection progressed. Figures 2, 3 and 4 show the three surfaces of the tibia with the arteries in red and the veins in blue.

On the posterior surface of the tibia the popliteal artery sends off a medial and a larger lateral branch, both of which encircle the head of the tibia at the periphery of its upper articular surface.

The medial branch, the deep medial genicular artery, is represented by a single or double vessel which runs medially on the femoro-tibial part of the joint capsule supplying the capsule, finally anastomosing with the descending genicular artery (Miller)\(^ {39} \).

The specimen from which fig. 2 was drawn showed a single deep medial genicular artery from which a ventrally directed branch arose to supply the posterior surface of the joint capsule. A dorsally directed branch entered the M. semimembranosus, where it possibly anastomosed with the descending genicular. The major portion of the blood supply carried by the vessel in question, in this particular specimen, was distributed to the foraminae of the lateral aspect
of the medial epicondyle of the tibia. Periosteal branches of the deep medial genicular artery were distributed to the postero-medial aspect of the medial epicondyle of the tibia and anastomosed freely with periosteal vessels originating directly from the popliteal artery. These vessels were found under the insertion of the M. popliteus. Satellite veins accompany all the arteries described.

From the lateral genicular artery a periosteal vessel descends under the lateral genicular vein to the head of the fibula where it gives off a branch between the origins of the M.M. flexor hallucis longus and tibialis posterior. This supplies the postero-lateral surface of the fibular head. This lateral fibular periosteal vessel continues distad on the lateral surface of the fibula along the anterior border of the M. flexor hallucis longus to anastomose in the middle of the fibula with a periosteal branch which arises from a muscular branch of the anterior tibial artery. The muscular artery continues from the anastomosis in the middle of the fibula to the distal third of the bone, where it enters the belly of the M. fibularis brevis. Transverse branches from this artery arise anteriorly and posteriorly along its entire length to anastomose with similar branches of periosteal vessels which lie on the medial surface of the fibula.

In the popliteal notch a number of arteries arise from the popliteal artery to enter the popliteal surfaces of both the medial and lateral tibial epicondyles. Corresponding veins leave foraminae
on the epicondyles to enter the popliteal vein.

At the distal end of the upper tibial epicondyles, the posterior tibial artery is given off from the popliteal artery. From the posterior tibial artery a periosteal artery descends along the lateral border of the origin of the M. flexor digitalis longus, between that muscle and the M. tibialis posterior. This vessel anastomoses, just below the midshaft of the tibia, on the postero-medial aspect, with an ascending periosteal artery which originates from the peroneal artery. Shortly after leaving the posterior tibial artery this vessel sends a muscular branch to the M. fibularis longus, and a few millimeters proximal to the nutrient foramen an anastomotic branch joins the lateral tibial periosteal vessel just beyond the point where that vessel leaves the nutrient artery. Transverse twigs leave the medial and lateral borders of this posterior tibial periosteal vessel to anastomose with similar vessels given off by the popliteal periosteal artery, and the lateral tibial periosteal vessels. These anastomoses form characteristic rectangular patterns from the borders of which minute vessels supply the periosteum within the rectangle (fig. 5). This posterior tibial periosteal artery, accompanied by its satellite vein, anastomoses with the ascending periosteal artery on the postero-medial surface of the tibia just below the midshaft.

About four millimeters distal to the origin of the posterior tibial periosteal artery, the posterior tibial artery gives off another obliquely descending periosteal artery, which courses between the insertion of the M. popliteus and origin of the M. flexor digitalis
longus along the popliteal muscular line, just below the level of the nutrient foramen on the postero-medial aspect of the tibia. This vessel, the popliteal periosteal artery changes its course, making a more abrupt descent, and anastomoses shortly thereafter with an ascending periosteal artery from the peroneal artery.

A branch of the popliteal periosteal artery and its satellite vein continues obliquely to the postero-medial surface of the tibia where it anastomoses with an ascending artery on the posterior surface of the tendon of the M. flexor digitalis longus.

From the transverse anastomotic artery between the posterior tibial periosteal and the nutrient arteries, the lateral tibial periosteal artery arises. This vessel descends medial to the nutrient foramen then along the medial side of the interosseous space to the fibular notch, from which it descends between the tibia and fibula on their posterior surfaces to the tarsal ends of the bones. At the upper end of the distal third of the tibia, an anastomotic branch of the lateral tibial periosteal artery descends obliquely toward the medial surface of the tibia where it anastomoses with the peroneal artery about one centimeter from the point where that vessel emerges from beneath the tendons of the MM flexor digitalis longus and tibialis posterior. Transverse twigs anastomose between the lateral tibial periosteal artery and the posterior tibial periosteal, ascending periosteal, and peroneal arteries.

The most distal periosteal vessel of the posterior surface of the tibia is the terminal portion of the peroneal artery. On
emerging from beneath the tendons of the M.M. flexor digitalis longus and tibialis posterior, the peroneal artery sends off the ascending periosteal artery along the postero-medial aspect of the tibia. About two millimeters distal a medially directed artery arises, and passes under the tendons of the M.M. flexor digitalis longus and tibialis posterior to descend along the medial surface of the tibia and enter the medial malleolus.

Two millimeters further distad, a periosteal artery is given off to descend posterior to the tendons of the M.M. flexor digitalis longus and tibialis posterior, finally entering the medial malleolus posterior to the tendon.

A third descending periosteal artery arises from the peroneal artery in the middle of posterior surface of the tibia and descends to the tarsal joint after sending a transverse branch to the previous branch. The final twigs of the peroneal artery are distributed to the distal end of the fibula on its posterior surface.

On the lateral aspect of the tibia and fibula (fig. 3) the lateral genicular artery gives rise to the lateral fibular periosteal artery proximal to the head of the fibula. The course of this vessel has already been described.

Immediately on emerging from under the fibula, the anterior tibial artery gives rise to two or three small arteries which ascend and divide into several branches which pierce the lateral aspect of the lateral tibial epicondyle. One millimeter distal to the lowest
of these vessels an artery arises, which courses in a cranio-proximal direction and sends anastomotic branches to the lateral fibular periosteal, lateral genicular, and the lateral genicular periosteal arteries.

The nutrient artery leaves the anterior tibial artery at a variable position in the interosseous space, descends along the posterolateral border of the tibia medial to the interosseous ligament, and finally enters the nutrient foramen. This vessel may be duplicated. A number of periosteal vessels leave the nutrient artery and supply the region around the nutrient foramen. Within the first centimeter from the point where the anterior tibial artery emerges from under the fibula, a large periosteal artery is given to the lateral surface of the proximal end of the tibia. Some of its branches enter the lateral epicondyle of the tibia, finally ending at the tibial crest. The descending branches of this artery often anastomose with a more distal periosteal branch which also supplies the lateral surface of the proximal end of the tibia. A number of small branches supply the M. tibialis anterior.

A small arterial twig crosses the interosseous space and supplies the M. flexor hallucis longus, often making a minor contribution to the periosteum of the proximal fibula.

Numerous arterial twigs arise from the anterior tibial artery at the level of the nutrient foramen to supply the M.M. tibialis anterior, extensor hallucis longus, and extensor digitorum longus. The most distal branch of the anterior tibial artery to the
M. tibialis anterior sends a muscular branch to the M. fibularis brevis. The anterior fibular periosteal artery arises from this vessel on the lateral surface of the M. flexor hallucis longus at the midshaft of the fibula. Here, minor twigs are sent to the lateral fibular periosteal. The major portion of this artery descends along the anterior surface of the fibula, passes between two venules, and thence descends to the junction of the middle and distal thirds of the fibula. Here it anastomoses with a branch of itself which arose at the midshaft of the tibia and descended along a parallel course on the lateral surface of the tibia. Two branches descend from the anastomoses to the lateral malleolus in their original direction, thence to the foot. At the lateral malleolus both vessels enter the distal coronary circulation of the tibia which extends around the bones. From this coronary circulation a number of small branches supply the periosteum and enter the bone.

The medial aspect of the tibia (fig. 4) presents the most intricate pattern of periosteal vessels. On this surface of the bone nearly all of the periosteal vessels arise from the saphenous artery or its branches.

The proximal quarter of the medial surface of the tibia is supplied by two strata of blood vessels. The superficial stratum consists of a network of vessels in the fat and subcutaneous fascia of the region. These vessels arise from the superficial medial genicular and a cutaneous branch of the saphenous artery which leaves about one centimeter distal to the origin of the superficial medial
geniculate artery. Both the superficial medial genicular and the cutaneous arteries branch and anastomose freely with each other. From the deep surface of the vascular network thus formed periosteal vessels supply the medial surface of the tibial head. Some of these periosteal branches enter foraminae distal to the upper tibial articulation.

In addition to the vessels from the saphenous artery, branches of the deep medial genicular artery (not shown in fig. 4) also supply the medial surface of the head of the tibia. Most of these branches enter the bone on the lateral surface of the medial epicondyle.

About two centimeters distal to the origin of the superficial medial genicular artery, the saphenous artery divides into its dorsal and plantar branches. About three millimeters distal to this bifurcation, an artery leaves the anterior surfaces of the plantar branch of the saphenous artery, dips under the dorsal branch of the saphenous, and goes to the posterior border of the "medial tibial ligament", which is the combined insertions of the M.M. gracilis and semitendinosus. Here, it divides into an ascending fascial branch and two descending branches. One descending branch adheres to the posterior border of the "medial tibial ligament" and sends off superficial, anteriorly directed twigs which anastomose on the surface of the ligament with twigs from a similar vessel on the anterior border of the ligament. The other descending branch courses on the lateral surface of the first branch, sending anterior periosteal twigs to the vessel on the anterior border of the "medial tibial ligament" (the ant-
ero-medial tibial periosteal artery), and posterior periosteal twigs to the popliteal periosteal artery - a branch of the posterior tibial artery. The ascending branch anastomoses with the medial genicular periosteal artery. About one centimeter below the midshaft of the tibia, the descending vessels anastomose with each other and with a branch of the peroneal artery which arises about a half centimeter from the point where that vessel dips under the tendons of the M.M. tibialis posterior and flexor digitalis longus.

From the confluence of these vessels two arteries descend in a craniad direction to anastomose with a branch from the dorsal branch of the saphenous artery.

The peroneal artery distributes a periosteal vessel about three millimeters from the point where it goes under the tendons of the M.M. flexor digitalis longus and tibialis posterior. This vessel descends obliquely across the distal end of the medial tibial ligament, then plunges distad from the anterior border of this ligament, under the annular ligament, to the medial malleolus where it enters the distal coronary circulation of the tibia and contributes intraosseous branches to the malleolus. The plantar branch of the saphenous artery supplies a branch to the distal coronary circulation of the tibia. It is interesting to note that this vessel, which lies on the midline of the medial surface of the distal third of the tibia, is the only periosteal artery on the posteromedial aspect of the tibia at its distal extremity, with the exception of the terminal branches of the peroneal artery and one minute branch to the tendon sheath of the M.M. tibialis posterior and flexor digitalis longus.
At about the midshaft of the tibia, the dorsal branch of the saphenous artery sends a periosteal vessel distad and proximad to the anterior aspect of the medial malleolus and the region of the tibial crest along the anterior border of the "medial tibial ligament". This anteromedial tibial periosteal artery anastomoses with branches from the peroneal artery and distributes anterior and posterior twigs to adjacent vessels. At the distal end of the tibia it supplies introsseous vessels and continues to the soft tissues of the tarsus.

A major contribution to the anterior tibial periosteal artery, which lies along the anterior border of the M. tibialis anterior, is derived from the dorsal branch of the saphenous artery at about the midshaft of the tibia, some three millimeters distal to the origin of the anteromedial tibial periosteal artery. The anterior tibial periosteal artery arises at the tibial crest from a confluence of arterial branches from the lateral genicular periosteal artery, the medial superficial genicular artery, and cutaneous arteries of the medial aspect of the head of the tibia. The vessel descends along the anterior border of the M. tibialis anterior on the anterior surface of the tibia to enter into the distal coronary circulation of the tibia.

A number of periosteal twigs leave this vessel from its lateral and medial surfaces, and muscular twigs leave from its anterior surface.

In addition to the major periosteal vessels and their characteristic rectangular formations on the surface of the periosteum,
the periosteal vessels branch into minute vessels towards the central area of the rectangle, (fig. 5) and also distribute intracortical vessels which pierce the external surface of the cortex (fig. 6).

The periosteal blood supply of the posterior aspect of the tibia was derived from the popliteal artery in the upper two-thirds and from the peroneal artery in the lower third of the bone. The anterior tibial artery supplied the lateral aspect of the periosteal circulation of the tibia. The medial periosteal circulation of the tibia was derived from the saphenous and peroneal arteries. The upper epiphysis of the tibia was supplied by the superficial medial genicular, deep medial genicular, lateral genicular, and popliteal arteries. These vessels are arranged in a coronary pattern around the upper tibial articulation. The distal epiphysis derived its blood supply from a distal coronary circulation which originated from the plantar branch of the saphenous artery, the peroneal artery, and descending periosteal arteries from all three aspects of the tibia.

The Medullary Blood Supply

The nutrient artery of the tibia enters the nutrient foramen at about the level of the distal end of the tibial crest. The nutrient foramen runs distad at an acute angle for a distance of about one centimeter before entering the medulla. Once in the medulla the nutrient artery veers toward the axis of the tibia and almost immediately divides into several proximal branches and one distal
branch. One proximal branch was found to ascend in the anterior corner of the triangular medulla to about the level of the tibial crest, where its final ramifications are distributed. The remaining two or three ascending branches of the nutrient artery were usually quite evenly dispersed in the substance of the medulla, but there was often one branch ascending over part of its course in the lateral corner of the medulla. All the ascending branches of the nutrient artery anastomosed at the level of the proximal end of the tibial crest with descending metaphyseal vessels.

The descending branch of the nutrient artery divides at the junction of the middle and distal thirds of the tibia into two to four branches, each of which further divide into a number of smaller branches. In the specimens examined it appeared as though the ramifications of the descending portion of the nutrient artery varied in pattern according to the age of the dog. In dogs with ununited epiphyses, these vessels were dispersed between the newly formed trabeculae of the distal end of the diaphysis to form a transverse network on the diaphyseal surface of the epiphyseal plate. In older dogs the nutrient artery was distributed to the cancellous bone of the distal end of the tibia and anastomosed freely with the metaphyseal vessels (fig. 7).

It is known that the nutrient artery distributes periosteal branches before it enters the nutrient foramen. In some specimens the nutrient artery has associated blood vessels in its adventitia. These vessels enter the nutrient foramen with the nutrient vessels and ramify
in the cortex immediately surrounding the nutrient foramen (fig. 8). They enter into the Haversian vascular system.

In some experiments in which the periosteum was not stripped or the intact nutrient artery incompletely cleared of fascia, these vessels were injected with latex, markedly hypertrophied, and apparently extended more distal than normal. Even in the presence of thrombosis of the nutrient artery, these periosteal vessels were seen coursing through the nutrient foramen.

It is assumed that these periosteal vessels in the nutrient foramen are arteries, and it is conceivable that medullary revascularization could occur in more than three weeks as a result of the changes which occur in these vessels after trauma to the nutrient artery.

The Blood Supply of the Cortex

Along its entire length the branches of the nutrient artery distribute innumerable vessels which supply the substance of the medulla and the cortex. These vessels leave the medullary artery almost at a right angle to the long axis of the bone, and their numbers give the artery a "bottle brush" appearance. This pattern of vascular distribution occurs in the radius and femur of the dog and appears to be the characteristic vascular pattern of the medulla of the long bones. After traversing the medullary substance the transverse branches of the medullary artery are found to enter the cortex from its internal surface and as they traverse the thickness of the
cortex, branch into the many Haversian vessels. The larger transverse vessels pierce the entire thickness of the cortex to emerge on the external surface and anastomose with the periosteal arterioles. A similar arterial distribution arising from the periosteal arteries enters the external surface of the cortex and is dispersed to the Haversian system. The venous drainage of the cortex arises from the Haversian system and flows either to the medulla or the periosteum (figs. 9).

The Metaphyseal Blood Supply

The blood supply of the ends of the tibia of the dog arises from numerous vessels which enter foraminae on all surfaces of the upper end of the diaphysis, the upper tibial epiphysis, the tibial tuberosity, tibial crest, distal end of the diaphysis, and the distal tibial epiphysis.

The upper tibial epiphysis and the proximal end of the diaphysis receive blood from the lateral, deep medial, and superficial medial genicular arteries on their lateral and medial borders respectively. The posterior aspect of the upper epiphysis and the upper end of the diaphysis are supplied by arterial twigs from the popliteal artery as it passes through the popliteal notch.

The tibial tuberosity derives its arterial blood supply from the terminal branches of the deep medial genicular artery, the lateral genicular artery, and the lateral fibular periosteal artery (fig. 10). The anterior tibial periosteal artery sends a twig into a foramen of the tibial crest. This vessel anastomoses with the most anterior branch
of the ascending portion of the medullary artery.

The distal ends of the tibia and fibula are supplied with arterial blood on all sides by the intraosseous branches of the distal coronary circulation of the tibia, and by the terminal branches of the peroneal artery on the posterior aspect of the medial and lateral malleoli (fig. 11). In the young animal the metaphyseal vessels form a network in the region of the epiphyseal plate (fig. 12).
Methods

The injection series of experiments was designed in an attempt to show whether the shaft of a bone, in this case the tibia, is dependent on any source of blood supply, or if bone will survive after the interruption of one or two sources of blood supply. In this series of experiments the central portion of the tibial shaft was deprived of the blood from two of its three sources, the metaphyseal or a nutrient or periosteal supply remaining intact in one of the experiments. The converse of each experiment was done as a check. A waiting period of three days between the interruption of the source of blood supply and the injection of the specimen was allowed. This waiting period would allow thrombosis of severed arterioles to occur and thus eliminate the injection of ruptured vessels. The three-day waiting period would not be long enough to permit revascularization of devascularized bone. However, in view of experiments done by Murry (1941), wherein he showed that revascularization of a fracture commenced at twenty-four to thirty-six hours, it was deemed expedient to discourage such revascularization by the insertion of "teflon" between the interrupted source of blood supply and the portion of the tibia under study.

Histological studies were not undertaken in this series of experiments because injection of the vascular pattern could be seen in cleared specimens, and because it is extremely difficult to inter-
pret the presence of bone death at three days.

Table I shows the number of tibias involved in each experiment, and the sources of blood supply that were interrupted.

**TABLE I**

<table>
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The figures in Table I represent those experiments which were successfully completed. Thrombosis of the nutrient artery, probably as a result of stretching, was frequently encountered and resulted in the elimination of eight animals from this series.

Results

In the intact tibia the vascular pattern appeared to be the normal one. A description of the normal blood supply of the tibia can be found under the heading "Controls". When all three sources of blood supply to the central portion of the tibia were removed and the isol-
ated segment of bone was encased in a "teflon" envelope, it was found, as expected, that there was no injection of the vascular pattern of the bone. This result was also achieved in the absence of the "teflon" envelope when the stripped periosteum was replaced around the cortex and no plastic was interposed between the isolated segment of bone and the proximal and distal fragments of the tibia.

In the absence of the nutrient artery but with an intact nutrient vein, the injected specimen showed what appeared to be a normal vascular pattern. It was found that the metaphyseal and periosteal vascular components of the tibia were normal and the nutrient vein filled, but that the nutrient artery remained empty (fig. 13).

The presence of the nutrient artery as the sole source of blood supply to an isolated segment of the tibia resulted in the filling of the medullary and Haversian vessel of the isolated segment. From the medullary vessels transverse arterial twigs could be seen entering the medullary surface of the cortex and some of these continued through the cortex to its external surface (fig. 14). The nutrient foramen showed vessels entering the cortex (fig. 15). These could be of periosteal origin.

Stripping of the periosteum in the presence of intact nutrient and metaphyseal vessels resulted in injection of the medullary vessels and the Haversian system of the cortex. It is of interest to note that the cortical surface of elevated periosteum presented a characteristic "paint-brush" pattern of new blood vessels, some of which
were filled with latex and others with india ink.

The attached periosteum as the only possible source of blood supply to an isolated fragment of the tibial shaft showed thickening of the periosteum with an increase in the diameter of the periosteal vessels. The ends of the isolated segment of bone presented neovascular patterns which originated from the medulla. The medulla contained small vessels which were well injected with latex and india ink. These vessels could be seen piercing the cortex from the periosteum. The Haversian vessels contained india ink. Latex-filled vessels of periosteal origin entered the nutrient foramen but did not extend to the medulla.

When both the nutrient and periosteal sources of blood supply were intact and the metaphyseal source interrupted, there was periosteal thickening with hypertrophy of the periosteal vessels. The ends of the isolated segment showed the presence of neovascular structures. The medullary vessels were well injected with latex, in which small amounts of india ink were present. The nutrient vein could not be seen in these specimens.

When the sole source of blood supply to a segment of the tibia was the metaphyseal vessels, the nutrient vessels having been severed and the periosteum elevated, it was found that the medullary vessels were injected with both latex and india ink. The surface of the denuded cortex showed minute streaks of latex. This latex is thought to represent injected arterioles arising from the medullary vessels. It could not be determined whether these vessels were de-
scending or ascending as they emerged from the cortex.

In an attempt to show whether there were vessels entering or leaving the cortex of the tibia along the course of the nutrient foramen, isolated segments of bone, with the medulla plugged with bone wax and the nutrient vessels intact, were injected after a three-day waiting period. It was found that the nutrient artery thrombosed, and injection of this vessel was not accomplished. In no specimen in which the nutrient artery was injected was there any evidence that this artery gave rise to a portion of the cortical blood supply as it traversed the nutrient foramen. In these specimens there was poor injection of the Haversian system surrounding the nutrient foramen (fig. 16). This injection seemed to arise from the minute vessels on the surface of the nutrient artery. The remainder of the cortex was not injected.

The data gathered from the injection series of experiments described would suggest certain facts regarding the blood supply of the central portion of the tibia of the dog and would probably be applicable to the long bones in general.

Ligation of the nutrient artery resulted in no change in the vascular pattern of the tibia except the absence of filling of the nutrient artery. Drinker et al. made a similar observation in 1922. This would suggest that cortical circulation is adequately supplied and drained by the periosteal and/or the metaphyseal vessels. The filling of the nutrient vein is indicative of its draining of capillary beds supplied by either the metaphyseal and/or
the periosteal arteries. Because the nutrient vein is relatively small compared with the nutrient artery and could not be expected to drain the area of bone supplied by the nutrient artery, provided that nutrient arterial and venous pressures are not in the inverse ratio as their diameters, it follows that blood brought to the tibia by the nutrient artery must drain partially through either the metaphyseal or periosteal veins or through both. There is no reason to believe that the pressure within the nutrient vein is more than that within the artery. In fact this seems most unlikely in view of the histology of these structures.

It would be natural to conclude that bone, like other tissues, should have a satellite arrangement of arteries and veins. That the medullary arteries supply the cortex from within has been shown when the nutrient artery is the only source of supply to an isolated segment of bone (fig. 14). When the sole source of blood supply to the cortex is the periosteal vessels, there is hypertrophy of the periosteal vessels and injected vessels can be seen entering the medulla through the cortex. Vascularization of the cortex is present. The Haversian vessels are filled with india ink when either the nutrient supply or the periosteal supply is the only intact source of blood. It should, therefore, seem that the periosteal blood supply is capable of nourishing the cortex.

Stripping of the periosteum in the presence of intact nutrient and metaphyseal vessels resulted in good injection of the medullary vessels and Haversian vessels of the cortex. Minute foci of
latex situated two to three millimeters apart appeared on the outer surface of the denuded cortex. As it is thought that latex of the viscosity used does not traverse the capillary bed, the foci of latex on the surface of the cortex would represent arterioles emerging to the subperiosteal stratum.

When the metaphyseal plexus remained intact and the periosteal and nutrient vessels were interrupted the medullary vessels filled with latex and india ink. Medullary vessels could be seen entering the cortex and the Haversian system was injected, though poorly. It should seem then, that the metaphyseal vessels anastomosed with medullary vessels, as has already been suggested from the findings in the normal tibia. It should seem that good cortical vascularity is present when both the nutrient and metaphyseal vessels are intact in the absence of the periosteum.

The absence of only the metaphyseal vessels resulted in a well injected cortical vascular system, the pattern suggesting that the two remaining sources of blood supply were adequate for cortical maintenance.

In summary then, the facts gathered from the injection experiments seem to show that:

1. The periosteal vessels can adequately supply and drain the cortex.

2. The nutrient artery can adequately supply the substance of the medulla and the cortex.

3. The metaphyseal vessels anastomose with the medullary
vessels and only produces vascularization of the inner half of the cortex.

4. The nutrient and metaphyseal sources of the blood supply together supply the medulla and the entire cortex.

5. The periosteal vessels alone or with either the nutrient or metaphyseal vessels can adequately supply and drain the cortex.

6. Vessels of periosteal origin supplied and/or drained the cortex via the nutrient foramen.

No evidence was presented that the nutrient artery supplied the cortex in the nutrient foramen.
Methods

The physiological series of experiments was a repetition of the injection experiments in which an interval of three weeks was allowed between the interruption of the various sources of the blood supply of the tibia and injection of the specimen. In all instances the specimen was injected via the femoral artery with gelatin and india ink followed by diluted latex. The presence of the latex made identification of injected vessels possible in uncleared specimens. The latex was dissolved by the methyl salicylate so that cleared specimens only occasionally showed free pigment within the vessels.

Table II shows the combination of vessels removed and the number of tibias represented in each experiment.

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Histological sections and cleared sections were made from
several areas of all specimens. A gross examination of uncleared sections was made to determine the presence of injection with latex. In this series of experiments the criteria of bone vascularity used were the presence of injection media, as well as the presence of living osteocytes.

Results

When the nutrient artery was the only source of blood supply to an isolated segment of bone it was found that the medullary vessels were well injected and endosteal callus was present. The vessels of the medulla entered the cortex and were distributed primarily to the inner half of the cortex, though some latex-filled vessels traversed the cortex and appeared on its outer surface (fig. 17). The outer half of the cortex appeared to be normal with injection of the Haversian vessels throughout the cortical thickness. Surrounding the nutrient foramen and within the "teflon" envelope an area about one centimeter in diameter was seen which showed callus formation. It was thought that this area represented incompletely stripped periosteum which had revascularized from the periosteal arteries along the surface of the nutrient artery. Surrounding the isolated central segment of bone two millimeters of callus were seen which extended somewhat beyond the extremities of the denuded cortex.

An intact periosteum as the only source of blood supply to an isolated segment of the tibia resulted in three weeks in hypertrophy of the periosteal vessels with two millimeters of callus surr-
ounding and intimately associated with the cortex. The medullary vessels were well injected and the cortex showed periosteal arteries entering and ending in the medullary circulation. Endosteal callus was present. The cortex was well injected and the osteocytes appeared to be alive (fig. 18).

In the presence of both nutrient and metaphyseal vessels with an elevated periosteum, there was two millimeters of callus surrounding the denuded portion of the cortex. The medulla was well injected with both latex and india ink. The vessels from the medulla were seen to penetrate the cortex to its external surface where they formed islands (pannus) of latex and india-ink-injected vessels two to three millimeters in diameter (fig. 19). The cleared specimens showed injection of the complete cortex with india ink and latex (fig. 20). Because of the solubility of latex in methyl salicylate, it is not possible to visualize the latex-injected vessels as clearly as those injected with india ink, it was therefore not possible to say what relationship there was between these two sets of vessels. Bone death was not evident in the cortex.

When the metaphyseal vessels are the only source of blood supply to a portion of the tibial cortex there was the expected periosteal reaction with callus formation surrounding the segment of bone. The medullary vessels were well injected as was the cortex on its inner half. The cortex appeared dead in its outer half. Endosteal callus was present.

The nutrient and periosteal vessels together resulted in
injection of the medulla with latex and india ink. Vessels from the periosteum and medulla were seen to traverse the entire thickness of the cortex. Endosteal and periosteal callus was evident throughout the length of the isolated segment of bone. The Haversian vessels were well injected, and there did not appear to be any bone death.

With only an intact periosteal blood supply and with the medulla plugged with bone wax, the changes in the isolated segment at three weeks were hypertrophy of the periosteal vessels with the deposition of approximately three millimeters of callus which was adherent to the cortex. Periosteal vessels revascularized the nutrient foramen in its upper half. The Haversian vessels were not injected in any portion of the cortex, which appeared to be dead. The entire cortex was lacking in osteocytes and was assumed to be dead. There was evidence of commencement of revascularization of the dead cortex (fig. 21).

When the nutrient vessels were severed and the medulla plugged through the proximal end of the tibia, it was found that about two millimeters of callus formed around the entire shaft of the tibia as far distal as the medullary plug extended (fig. 22). The periosteal vessels were hypertrophied and the cortex was completely avascular. Cortical death was present throughout the bone and there appeared to be an attempt to revascularize the dead cortex. The periosteum was very easily elevated. It is possible that the trauma of surgery could have produced some of the periosteal response even
though the damage to the periosteum was considered negligible; however, a limited area should have been involved.

The complete removal of a segment of bone from the tibia and its replacement without a "teflon" barrier to any of the sources of blood supply resulted in the formation of periosteal callus particularly on the lateral aspect of the bone. This callus was adherent to the cortex but did not supply blood to any portion of the cortex. The osteocytes of the entire cortex were absent and the medulla was necrotic.
GENERAL DISCUSSION

The Periosteal Plexus

It should seem, from the observation of this work and the work of Brookes and Harrison, that the periosteum of the tibia is supplied by specific arteries which arise from definite locations on the arteries of the limbs. Brookes and Harrison describe periosteal arteries in the rabbit tibia which correspond to the arteries which have been referred to in this paper as the lateral tibial periosteal, posterior tibial periosteal, anterior tibial periosteal, lateral fibular periosteal arteries, and the distal coronary circulation of the tibia. It may be noted that the diagrams of the periosteal circulation of the tibia in the article by Brookes and Harrison seem to be incorrectly labelled posterior and anterior. Many discrepancies with regard to the nomenclature of the major arteries of the lower limb exist between this paper and that of Brookes and Harrison.

The venous drainage of the tibial periosteum in the dog shows a satellite relationship with the arteries. These findings are contrary to the opinion expressed by Starr. Kolodny's separation of the soft tissues surrounding the periosteum of the radius of the dog so as to devascularize the periosteum would presuppose that the soft tissues were the source of periosteal vascular supply. That this is not the case in the tibia of the dog has been shown. The periosteal vessels appear to be distinct from the muscular vascular-
ization. In the dissection of the specimens for this work, it was found that the periosteal vessels in the regions of muscular attachments passed through muscle tissue and perhaps supplied twigs to the muscles, but could never be said to originate from the muscular vascularization. This was particularly true in the sulcus muscularis of the tibia. The most distal artery to the M. tibialis anterior distributes the anterior fibular periosteal artery, which in turn distributes a twig to the lateral fibular periosteal artery just below the midshaft of the fibula. From this point of anastomosis to some three centimeters distal, the lateral fibular periosteal artery is enveloped in the tissue of the M. fibularis brevis and supplies twigs to both the periosteum and this muscle. Finally the lateral tibial periosteal artery ramifies in the M. fibularis brevis (fig. 2).

This then is an instance in which muscle is supplied by a periosteal artery. It cannot be denied that muscle insertions are intimately related to the periosteal vascular plexus, but this relationship was only observed to exist to the extent that the periosteal vessels were distributed in the inter-muscular septa, as it were, along the lines of least resistance.

The peculiar tendency of the distal third of the tibia toward non-union of fractures has been of interest to orthopaedists for some time. It may be noted (figs. 3 and 4) that in these dissections the periosteal blood supply of this portion of the bone is largely dependent on the peroneal artery on the posterior and most of the medial surfaces of the bone. Injury to this subcutaneously placed peroneal
artery could have dire consequences on the healing of a fracture. In addition to the dependence of nearly two-thirds of the circumference of the distal tibia for its periosteal blood supply on the peroneal artery, all specimens dissected seem to possess less distinct anastomoses of the transverse periosteal twigs on all surfaces of the distal portion of the tibia (figs. 23 and 24) than were present in the periosteum of the upper portion of the tibia (fig. 25).

The Medullary Blood Supply

Having passed into the medulla, the nutrient artery, almost immediately, divides into ascending and descending medullary branches. These medullary arteries subdivide and continue to the metaphyses. Along their courses to the ends of the bone the medullary vessels distribute transverse branches to the cortex (fig. 9). These will be discussed later. In the young dog the medullary arteries supply the diaphyseal side of the epiphyseal plate and can be seen to anastomose with the metaphyseal plexus of vessels (fig. 12). The tibia of the mature dog shows the absence of vascular pattern at the epiphyseal plate and obvious anastomosis between the metaphyseal and medullary vessels (fig. 11). This is contrary to Harris'21 view that the diaphyseal terminal arteries are end arteries.

Johnson's27 finding that a metaphyseal injection filled the entire bone with the exception of a slight central diaphyseal deficiency would suggest that there is the presence of an anastomosis between the metaphyseal and medullary vessels, and that the cortex is supplied by the
medullary vessels. This fact was borne out in the injection of the tibia three days after the removal of the nutrient and periosteal vessels. At three weeks a bone prepared in this manner shows fully injected medullary vessels and obvious injection of the cortex. Such a preparation, however, shows death of the osteocytes in the outer half of the cortex of the central portion of the diaphysis.

Drinker et al.\textsuperscript{13} showed that the injection of a specimen with a ligated nutrient artery was as complete as one in which the nutrient artery alone was injected. This was shown to be true in injections made immediately or three days after the nutrient artery was obliterated (fig. 13). The only difference between the immediate and three-day injections was that the nutrient artery was incompletely filled from the medullary arteries though the nutrient vein was completely injected.

Huggins and Wiege\textsuperscript{25} produced ischaemia of the bone marrow by rupturing the nutrient artery and found that this ischaemia was overcome in seventy days.

Kolodny\textsuperscript{30} made the observation that the medullary vessels are always ruptured in a complete fracture of the diaphysis. This is obviously true and would mean that portions of the diaphysis which did not contain the nutrient artery would be subject to necrosis were it not for the anastomosis between the metaphyseal and medullary vessels. That this portion of the diaphysis, deprived of connection with the nutrient vessels, does not necrose is common knowledge. Furthermore Lexer\textsuperscript{33} and Drinker et al.\textsuperscript{13} observed that a fracture of the
diaphysis did not allow injection across the fracture line and that the fragment remote from the nutrient artery contained injected medullary vessels which could only have been filled via the metaphyseal plexus. Brookes showed that the absence of nutrient vessels does not interfere with the existence of medullary vessels.

In summary then, the medullary vessels arise from the nutrient artery and anastomose with the metaphyseal plexus in the ends of the diaphysis. In the event of separation of the medullary vessels from the nutrient source of supply or even the absence of nutrient vessels, the medullary vessels are present and patent; though from the findings of Huggins and Wiege it should seem that for some time the metaphyseal plexus was an inadequate collateral supply to the medulla. This is assuming that the periosteal vessels do not supply the medulla as Brookes and Harrison suggest in the case of the rabbit.

The Metaphyseal Plexus

In the dog the metaphyseal plexus of the upper end of the tibia originates from the lateral genicular, superficial and deep medial genicular, and the popliteal and the anterior tibial arteries. The distal portion of the metaphyseal plexus of the dog's tibia arises primarily from the peroneal artery and the distal coronary circulation, which receives contributions from the periosteal vessels that descend to this end of the bone.

It has been shown that the metaphyseal vessels anastomose
with the medullary circulation, are by themselves inadequate for the
nutrition of the medullary substance, but that they will eventually
establish an adequate collateral circulation to the medulla. Here
again, it is assumed that the periosteal circulation does not supply
the medulla. In the dog the metaphyseal vessels alone appear to
supply adequate nutrition for maintenance of the bone marrow of the
tibia.

In the young dog the metaphyseal vessels supply the epiph-
ysis of the tibia and the tibial tuberosity, anastomotic branches
being distributed to the diaphyseal side of the epiphyseal plate.

The Cortical Blood Supply

The result produced by the removal of one or more of the
three sources of blood supply of bone has been the principal method
of studying the blood supply of the cortex. After various waiting
periods the response elicited from the bone has been studied by in-
jection techniques, radiographic methods, histological techniques,
and by means of radioactive tracers. All these methods have faults,
and none of them can be relied upon to produce accurate results. Un-
reliable results are produced with greater frequency when a secondary
response is used as the criterion to determine the primary effect.

The vascular pattern of the cortex, its sources of supply,
and the routes by which it drains into the general venous circulat-
ion, are perhaps the least known features of bone. It has been
shown that the medullary vessels which are of nutrient origin anast-
omose with the metaphyseal vessels and that the periosteum is vascular and with the medullary vessels constitutes the potential sources of cortical vascular supply and drainage.

The questions which arise are (1) Does the nutrient artery supply the cortex as it traverses the nutrient foramen? (2) Does the periosteum supply or drain the cortex? (3) Do the medullary vessels supply or drain the cortex? (4) How much of this blood supply to the cortex can the bone be safely deprived of? An attempt will be made to answer these questions on the basis of the experiments performed in this work.

The nutrient artery arises from the anterior femoral artery, courses distad parallel to the posterolateral border of the tibia, and enters the tibia at the junction of its upper and middle thirds. From its external portion periosteal vessels are distributed to the region immediately surrounding the nutrient foramen and more distal regions, via the lateral tibial periosteal artery. It is possible that on its course through the nutrient foramen the nutrient artery could distribute branches to the Haversian system. In these experiments no such arterial twigs were observed. Minute injected arterial structures were, however, seen on the adventitia of the ligated, uninjected nutrient artery when the ligation was done immediately before injection (fig. 8). These vessels arose from the proximal end of the nutrient artery above the ligature, and entered the nutrient foramen. In instances where the nutrient artery was the only supply to an isolated segment of the tibia and the medulla was plugged with bone wax for three days, these vess-
els were injected as were the Haversian vessels, the latter one millimeter from the nutrient foramen. The vessels extended from the nutrient foramen into the cortex (fig. 16). No other portion of the cortex was injected. A similar pattern of injection occurred at three days in the presence of a thrombosed nutrient artery as the only "source of supply" to an isolated segment of bone with an intact medulla. At three weeks the injection pattern was unchanged, but the medulla of the isolated fragment was necrotic and the cortex dead. The nutrient artery was never injected in these specimens. Even in the absence of a nutrient artery minute arteries arising from the intact periosteum were observed to enter the nutrient foramen, but these arteries were never found to continue to the medullary surface of the cortex.

It should seem then that the cortex receives a blood supply along the nutrient foramen and that this source of blood is not dependent on the presence of a nutrient artery but rather on the presence of periosteal arteries. It is true that some of the periosteal arteries which supply the cortex of the nutrient foramen originate from the upper end of the nutrient artery, but it cannot, in the light of these findings, be considered that the nutrient artery per se supplies twigs to the cortex in the nutrient foramen.

The presence of the periosteal blood supply to the cortex has been questioned by a number of workers who performed varied experiments. Johnson held the view that because the stripping of the periosteum did not alter the vascular pattern of injected bones, the peri-
osteal vessels did not extend below the cortex. It is true that the stripping of periosteum does not appear to alter the vascular injection of the cortex, but it is erroneous to conclude that this situation arose because the periosteum does not supply the cortex. The other possibility is that the cortex is not solely dependent on the periosteum for its blood supply. If the cortex was not entirely dependent for its vascularization on the periosteum, then depriving the cortex of this tissue would not produce infarction, as was found by Brunschwig in the adult dog. Merneffe found that the outer portion of the cortex of rabbits was dependent on the presence of an intact periosteum. This could mean that the outer portion of the rabbit cortex either has a "closed" circulation or that stripping of the periosteum destroys either its arterial supply or venous drainage. In view of the work of Brookes and Harrison from which they concluded that the cortex of the adult rabbit was not supplied by the periosteum but was drained primarily by the periosteum, it would seem likely that Merneffe interrupted the venous drainage of the outer position of the cortex. Wu and Miltner and Trueta produced increased length of the tibia of young rabbits by interrupting the periosteal and nutrient circulations for long periods of time. If Ferguson's finding holds true and Brookes and Harrison are correct in stating that the periosteum of rabbits does not supply the cortex, then it should seem that the increased growth occurred as a result of shunting the nutrient blood supply through the metaphyseal vessels.
In these experiments when only the periosteum was elevated complete injection of the bone was achieved which would substantiate Johnson's findings. Bone death was not observed, which is as stated by Todd and Iler.

Where the periosteum was the only possible source of supply to an isolated segment of bone with an intact medulla, the Haversian vessels were well injected and the medullary vessels showed the presence of latex which could only have originated from the periosteum. No evidence of cortical necrosis was present (fig. 18). This is contrary to the findings of Brookes and Harrison in the adult rabbit.

In the absence of the medulla, the nutrient vessels and the metaphyseal vessels, the bone presented quite a different picture. In this instance there was no injection of the Haversian vessels, and the cortex was dead and surrounded by a thick periosteal callus. At three weeks there was evidence of an attempt to revascularize the dead cortex. This picture of bone change was again apparent when the metaphyseal and periosteal vessels were intact with the medulla destroyed and the nutrient vessels severed (fig. 22).

It should seem that the cortex cannot be maintained by the periosteal circulation unless the medullary vessels are intact, this is probably because the periosteum supplies the medullary vessels which in turn supply the cortex; that the metaphyseal and periosteal vessels together do not constitute a circulation, and that the metaphyseal vessels cannot maintain the cortex in the absence of medullary vessels. These observations are of importance to the surgeon in
that an intramedullary pin which completely occludes the medulla will produce cortical death and afford periosteal union only. It would be expected that revascularization of the dead cortex would occur as though the cortex was an autogenous bone graft (Gallie and Robertson, 1919), and eventually be replaced by the process of "creeping substitution" (Bath 1893, 1894, and Marchand, 1899). A completely isolated segment of bone, devoid of all blood supply, will in effect be an autogenous bone graft and will be revascularized, resorbed and replaced. This was found to be the case and the periosteal new bone was found to be adherent to the isolated segment.

The stripping of the periosteum and removal of the nutrient vessels, leaving only an intact metaphyseal circulation to the tibia of the dog, resulted in injection of the medullary vessels as already stated. The Haversian vessels of such a specimen were injected only in the inner half of the cortex. Histological studies revealed that the outer portion of the cortex had undergone necrosis, a picture similar to that found by Merneffe. In instances where both the nutrient and metaphyseal vessels remained intact, there was injections of the medullary vessels, complete injection of the Haversian vessels of the cortex, and no necrosis of the cortex. These findings pertain only to the central portion of the tibial shaft which was examined and suggest that the metaphyseal circulation alone is able to maintain only the inner half of the cortex whereas the addition of the nutrient vascular supply will maintain the entire cortex.
The removal of the metaphyseal circulation from a segment of bone does not result in the death of the cortex or interfere with the injection of the Haversian system. This substantiates Kolodny's opinion in regard to the rupture of the medullary vessels in a complete fracture.

The nutrient vessels alone are capable of maintaining the central fragment of the tibia of the dog and producing complete injection of the Haversian vessels. This was suggested by the injection experiments of Drinker et al. and Johnson. Johnson considered the nutrient vessels of prime importance to the vascularization of long bones, and the metaphyseal plexus of secondary importance. The nutrient artery was not found to be essential to the nutrition of the rabbit femur (Brookes). It is true that the nutrient artery and its medullary branches can supply the entire long bone and that the metaphyseal vessels will achieve the same result provided that the medullary vessels are intact. However, it should seem from these experiments that the periosteal circulation, being capable of medullary and complete cortical maintenance, should be ranked in importance above the metaphyseal plexus. The fact that the periosteum is the prime osteogenic tissue in fracture repair should place its importance above that of the nutrient artery, which in addition is more subject to avulsion and has but one origin.

Because the periosteum alone can adequately maintain the cortex, there must be not only arterial, but venous routes in that circulation. It was noted that the nutrient vein was absent in some
experiments where the nutrient and periosteal arteries adequately supplied an isolated segment of bone. This could not occur unless the periosteum drained the capillary bed supplied by the nutrient artery.

Fig. 26 summarizes the information collected in this work on the gross blood supply of tibia of the dog. The metaphyseal vessels anastomose with the medullary plexus at both ends of the bone. The medullary vessels, which originate from the nutrient vessels, divide almost at the nutrient foramen sending several vessels proximad from that point. The descending medullary vessel divides at about the midshaft of the bone and again subdivides in its lower end. The medullary arteries supply the endosteum and medulla and the cortex from within. The cortex is drained via the medullary veins or the periosteal veins. The periosteal veins also drain the periosteum. Arteries of the periosteum enter the cortex directly to the medullary arteries and via these arteries can supply the cortex.
SUMMARY

In these experiments on the blood supply of bone it has been shown that:

1. The periosteal arterial circulation of the tibia is derived from specific vessels of the leg and is constant.

2. The venous drainage of the periosteum is essentially along the courses followed by the arteries.

3. Stripping of the periosteum does not inactivate the osteoblasts.

4. The periosteum alone can adequately supply and drain the cortex, provided that the medullary vessels are patent.

5. The periosteum probably supplies the medullary vessels which in turn supply the cortex.

6. The periosteum can drain the venous blood from the cortex and medulla.

7. The periosteum appears to supply the cortex around the nutrient foramen.

8. The periosteum will produce callus on the surface of an autogenous graft, and will revascularize it.

9. The metaphyseal vessels originate from the periosteum.

10. The metaphyseal vessels anastomose with the medullary vessels.

11. The metaphyseal vessels alone are incapable of main-
12. The metaphyseal and nutrient vessels together can maintain the cortex.

13. The medullary vessels distribute transverse twigs which supply the medulla, endosteum, and cortex.

14. The nutrient vessels are not essential to cortical maintenance.

15. The nutrient vessels alone can maintain the cortex.

16. Absence of only the medulla produces cortical death and a subsequent periosteal callus along the length of bone deprived of medulla.
ADDENDUM

The purpose of this section is to describe in detail the various methods used in carrying out the series of experiments in this work and the technical difficulties which arose. These difficulties may be avoided by someone repeating these experiments.

Surgical Techniques

Throughout the entire series of experiments the principles of aseptic surgery were carried out to the extent of preparing the skin, draping the leg completely, using sterile equipment, etc. Tissues were kept moist during surgery in order to eliminate cell death from dehydration. The skin incision extended from the femorotibial articulation on the medial aspect of the limb to the tarsus on its anterior surface. This line of incision was anterior to the dorsal branch of the saphenous artery, which it was felt necessary to preserve in view of the finding that the saphenous artery supplied considerable blood to the periosteum.

Stripping of the periosteum was carried out from a medial longitudinal incision with a periosteal elevator. In these experiments it was found that the periosteum of older dogs was more adherent to the cortex than that of young dogs; Starr mentions this fact in his book. It was also found that in the experiments where callus formation was rapid (plugged medulla and intact periosteum) the periosteum was very easily elevated. This observation is probably indicative of rapidly proliferating osteoblasts.
The nutrient vessels presented some difficulty when they were to remain intact in the presence of an elevated periosteum. The approach which was found most satisfactory was elevation of the periosteum from the medial aspect of the tibia to the point at which both borders of the M. flexor hallucis longus were visible, then separation of that muscle from the tibia at a point about three centimeters distal to the level of the tibial crest. Once that had been accomplished, the remainder of the muscular attachment was carefully freed with a periosteal elevator from the lateral and medial sides simultaneously. Visualization of the nutrient vessels was more easily done from the medial side of the leg. In instances where the bone was to be fractured the interosseous ligament was incised from the fibula notch to the point of distal fracture. A Gigli saw was passed between the bones, and the distal fracture made first. Stretching of the isolated nutrient vessels made it important to make the distal fracture first. The proximal fracture was accomplished after the nutrient vessels were protected with a pair of opened haemostats between the jaws of which the Gigli saw was passed.

Occlusion of the nutrient artery appeared to be related to the amount of movement of the isolated segment of bone, therefore every attempt was made to maintain reduction of the fragments throughout the procedure. It was also desirable to maintain reduction until injection of the limb was carried out.

Revascularization of the isolated segment of bone by means of the source of blood supply that had been removed was discouraged
by the interposition of a "teflon" sheet or the plugging of the medulla with bone wax. When the nutrient vessels were the only intact source of blood supply, these vessels were passed through a slit in the plastic, at the end of which a one-millimeter hole had been made to prevent vascular obstruction. The plastic completely enveloped the bone segment and was ligated in place with silk. In the presence of intact periosteum on an isolated segment of bone, the plastic barrier was ligated over the ends of the isolated segment. The plastic cuff or envelope was filled with isotonic saline to remove air bubbles which might have produced dehydration and tissue death.

The plugging of the medulla with bone wax was accomplished in isolated segments after the distal fracture was made and the proximal fracture almost completed. In the whole bone with a plugged medulla, wax was introduced through a hole drilled in the proximal end to the medulla. The medulla was first curetted and brushed clean; the wax was at room temperature and was forced into place with a stainless steel rod.

Immobilization of the fractured bone with elevated periosteum was accomplished with vitallium plates and screws which had previously been fitted to the proximal and distal fragment and removed before the fractures were made. The central fragment was ligated to the plate with silk (fig. 1). Where the periosteum remained intact immobilization was achieved with modified Thomas' splints.

Postoperatively, therapeutic doses of penicillin and streptomycin were given for four days by the intramuscular route to prevent
sepsis of the bones with impoverished blood supplies.

Injection Techniques

In preparation for this series of experiments, a number of specimens were injected immediately after death with warm 10% gelatin coloured with india ink, after the vessels had been flushed with isotonic saline. From these injections it was found that (1) muscular spasm was induced and the injections were poor, (2) the pressure at which good injections were done was not critical, and (3) it was extremely difficult if not impossible to differentiate between veins and arteries. As a result of these preliminary investigations it was decided at first to use an antispasmodic to overcome muscular spasm, but later this was found unnecessary if the injection was delayed for one hour after death. In order to establish which vessels were arteries and which were veins, some substance of particle size somewhat larger than a capillary was sought, but no satisfactory substance could be found. The decision to dilute latex was reached. Latex of approximately 56% was diluted 1:1 with ammonia water and extra pigment was added for colour. This produced satisfactory injection of arterioles down to those of the size of the transverse twigs of the periosteal arteries. This latex could not be demonstrated to pass into the capillary bed much less into the venous circulation. The injection of 10% gelatin with india ink followed by diluted latex resulted in filling of the veins and capillaries with gelatin and the arteries with latex. For the examination of un-
cleared sections this process was satisfactory; however, in the clearing process, it was found that latex was soluble in methyl salicylate. Polyvinyl acetate had the same disadvantage and was, in addition, difficult to use and produced poor injections.

The injection of specimens was carried out through the femoral artery after flushing of the vascular bed with 2.5% sodium citrate. The average dog required 80 to 100 cubic centimeters of gelatin followed by the same amount of latex to produce a satisfactory specimen. The injection was allowed to set at 40°F for 48 to 72 hours before dissection was attempted.

After the removal of muscles from the bone, decalcification was carried out in 5% nitric acid containing 5% formalin. This process was done on whole tibias and required about two weeks for completion. Smaller pieces of bone decalcified more rapidly. After decalcification the specimen was washed in cold running water for six to eight hours then dehydrated for 24 hours in each of 50%, 70% and 95% ethyl alcohol. Finally clearing was accomplished in methyl salicylate in 30 to 48 hours.

Sections were cut after decalcification, because dehydration hardens the specimen. It was found that sections of 0.5 to one millimeter were most suitable for examination at magnifications of seven to 20 diameters.
REFERENCES


The method by which the isolated central fragment was immobilized was a vitallium plate fixed to the proximal and distal fragments. The isolated, central segment was ligated to the plate.
Fig. 2

A drawing of the posterior aspect of the tibia and fibula of the dog showing the periosteal vascular pattern. The arteries are red and the veins blue.

1. Lateral fibular periosteal artery
2. Medial " "
3. Lateral tibial " "
4. Posterior " "
5. Popliteal periosteal artery
6. Ascending " "
7. Medial gonicular " "
8. Anterior fibular " "
Fig. 3

A drawing of the lateral aspect of the tibia and fibula of the dog showing periosteal vascularization. The arteries are red and the veins blue.

1. Lateral fibular periosteal artery
2. Lateral genicular " "
3. Anterior fibular " "
4. Anterior tibial " "
**Fig. 4**

A drawing of the medial aspect of the tibia of the dog. The arteries are red and the veins blue.

5. Popliteal periosteal artery
10. Antero-medial tibial periosteal artery
11. Anterior
Fig. 5. A photomicrograph of a portion of cleared periosteum showing an uninjected artery from which the latex has been absorbed, and in the venae comitantes injected with gelatin-india ink. The minute periosteal vascular branches are evident. Magnified x 40

Fig. 6. A photomicrograph of a longitudinal section of cortex showing a vessel leaving the cortex from the right and entering one of the venae comitantes at the left. Magnified x 40
A photograph of the distal ends of cleared tibiae of a young dog (left) and an adult dog (right). The medullary and metaphysical vessels are clearly shown in both specimens. These vessels can be seen to anastomose above the malleoli.
Fig. 8. A photomicrograph of a cleared unfilled nutrient artery with periosteal vessels on its surface. Magnified x 40

Fig. 9. A photomicrograph of the cortex and medulla showing the transverse twigs of the medullary vessels. Some of these transverse twigs can be seen on the endosteal surface of the cortex while others enter the cortex to supply the Haversian system. The large central vessel is thought to be vein draining from the cortex into the medulla. Magnified x 40
Fig. 10

A photograph of a cleared injected specimen of the upper end of the tibia of a young dog showing the vascularization of the ossification centers. A branch of the lateral genicular vessels can be seen in the region of the head of the fibula. A lateral fibular periosteal vessel enters the posterior aspect of the tibial epiphysis. From the anterior the tibial epiphysis receives vessels from the genicular vessels and the vessels of the upper metaphysis.
Fig. 11

A cleared distal end of the tibia of an adult dog showing the distribution of the medullary and metaphysical vessels within the cancellous bone.
Fig. 12

The distal end of a cleared tibia of a young dog. The anastomoses between the medullary and metaphyseal vessels is obvious. The vessels can be seen to form a plexus in the region of the epiphyseal plate.
Two cleared specimens in which the nutrient arteries had been ligated. Their vascular patterns appear normal. Both bones show injection of the nutrient veins. The ligature can be seen on the nutrient artery of the specimen on the left. There is no injection of the nutrient artery below the ligature. Minute vessels are present around the nutrient artery which was broken in handling.
Fig. 14
An isolated segment of bone with only a nutrient supply showing the injection of the medullary vessels, minute vessels entering the cortex and in the lower cortex one vessel can be seen traversing the cortex.
Fig. 15. Vessels which do not arise from the nutrient vessels supply or drain the cortex in the region of the nutrient foramen.

Fig. 16. Injection of the cortex surrounding the nutrient foramen was produced even when the nutrient artery was not patent.
Fig. 17
The nutrient artery alone as the source of blood supply to an isolated segment of bone produced a well injected medulla and cortex.
Fig. 18

A cleared cross section of the central portion of the tibia showing the vascularization of the cortex produced by the periosteal blood supply only. The medullary vessels are injected.
Fig. 22

A radiograph showing the formation of periosteal callus although entire lengths of the shaft in which the medulla has been occluded by bone wax. The periosteal and metaphysical vessels are intact.
Fig. 23

The anterior aspect of the distal end of the tibia showing the poor general vascularization of the periosteum and the noticeable scant transverse anastomoses between the periosteal vessels.
Fig. 24

The posterior aspect of the distal end of the tibia showing the poor vascularization. The peroneal vessels are evident descending from the upper left to the lower right.
Fig. 25

The posterior aspect of the central portion of the tibia showing the very vascular periosteum of this area. This specimen is the same as that of figs. 23 and 24.
A diagramatic sketch which shows the blood supply of the tibia of the dog as suggested by the experimental results achieved in this work.

1. Metaphyseal vessels
2. Nutrient vessels
3. Periosteal arteries
4. Periosteal vein
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Observation on the blood supply of bone in the dog.