Examination of the circulation in peripheral tissues has established the validity of certain theoretical hemodynamic concepts. The redistribution of blood flow between parallel vascular beds during unequal changes in their resistances seems to obey the general predictions of simple diversion. Such shifts of blood between vascular systems are exaggerated when the local perfusion pressure is diminished by abnormal upstream resistance. Diversion, as well as the deleterious effects of arterial occlusion, can be minimized if an adequate collateral circulation is established soon enough to prevent damage to the ischemic tissue. For tissues supplied by a true end artery, such collateral supply is ruled out by definition. Within the orbit the retinal artery is in fact an end artery while the ophthalmic artery may receive certain small collaterals. Redistribution of blood between the retina and the other orbital tissues is at least theoretically possible, and evidence for such a diversion should be sought in cases with clearly established partial occlusion of the ophthalmic artery. Since the retinal artery supplies only a single tissue, the diversions are limited to those between the various portions of the retina, or between a nutritive or shunt circulation. Evidence for the latter type of diversion has already been presented. We suggest that it might be of value to check these theoretical projections by direct experimentation insofar as possible; findings of such studies should assist us in describing the dynamics of intraorbital blood flows.

Diversions of blood flow to a dilated system of blood vessels at the expense of an undilated parallel system is most obvious where the pressure in the artery proximal to the bifurcation is significantly lowered. Normally the artery supplies sufficient blood flow to maintain adequate local pressure in the face of maximum tissue needs, i.e., when resistance falls to minimal levels. The pressure at any point in a peripheral artery is determined by three factors: central arterial pressure, resistance in the vessels upstream from the point under consideration, and total runoff through the distal branches. Thus, if all other factors remain constant, dilatation of any of the routes for runoff lowers the pressure at the arterial end of the parallel undilated beds and thus diminishes their perfusion. The pressure drop depends on the magnitude of the dilatation in the distal bed, but it is also influenced by the resistance central to the point. Normally, the resistance in the proximal arteries is insignificant; the major pressure drop occurs across the distal resistances, and dilatation of a peripheral bed has a minimal effect on the local arterial pressure. However, in pathologic conditions where resistance proximal to the branching constitutes a considerable fraction of the total resistance, increasing runoff lowers pressure to levels below the limits for which tissues can compensate. Only if a relatively unaltered pressure at the choice point can be assured, can blood flow in the undilated pathways be main-
tained. When a major artery is occluded or narrowed, restoration of pressure depends on the supply of more blood to the system distal to the occlusion via adequate collaterals.4

How existing or potential collateral circulation modifies local arterial pressure and hence diversion is a function of the relative amounts of flow through the original arterial supply and the new collateral system suggested by Fig. 1. The arrangements of alternative arterial pathways are morphologically varied.5 For example, the circle of Willis or the arches in the distal portions of the extremities, as in Fig. 2.a, unite several major arteries into a single system which then furnishes the blood to the tissues beyond. Frequently, only one of the arteries feeding the common path may suffice to satisfy the needs of the tissues beyond. In other situations only a potential alternative collateral pathway is present, i.e., small parallel arteries which ordinarily carry only a small fraction of the total blood to the tissue, but which dilate to provide an adequate collateral supply after occlusion of the major vessel. The mechanisms involved in opening of these vessels is still uncertain: Modification of the pressure gradient resulting from the drop in the distal portion of the original major artery must play some role,7 but other factors (chemical8 or nervous9) may intervene. Another type of collateral circulation carries blood around the occlusion through very small branches which connect with terminal portions of some other vascular trees. Because the hemodynamic resistance is quite high, blood flow through such pathways will be limited unless they are numerous, or the occlusion is at a point where the original resistance to the point of anastomosis was almost as great. Finally, in certain tissues true end arteries may exist, i.e., unique paths with neither real nor potential alternatives to supply the tissues (Fig. 2,b). Whether or not morphologically demonstrable end arteries exist in the body is still uncertain; the smaller coronary arterial branches have at times been considered as essential for supplying myocardial portions, but the conflicting data in this area leave the question again unresolved.10

The major blood supply to the orbit is through the single ophthalmic artery, the only major vessel entering through the foramen.11 Although some alternative pathways to this area are morphologically demonstrable, i.e., the ethmoidal vessels, from the internal carotid, and connections with the external carotid system might occur in the periorbital regions, there is still no evidence that such collaterals can satisfy the needs of all intraorbital tissues after occlusion or thrombosis of the ophthalmic artery.11

Obviously the concept of an end artery carries with it a description of the tissues which depend on that artery for their supply. Thus, as suggested by Fig. 3, the ophthalmic artery is an end artery with respect to the entire orbital contents, whereas the retinal artery is an end artery only for the retina. The practical significance of the collateral circulation is ultimately determined by the ability of the tissue to tolerate prolonged ischemia. To compensate for occlusion of the retinal artery, an adequate collateral circulation must manifest itself immediately, for only a few hours of complete ischemia of the...
Fig. 2. a, arterial supply to the hand with branchings and intercommunications that assure an adequate, preformed, collateral circulation. b, an end arterial system with no possibility for alternative supply of blood to any of the arterial branches.

Fig. 3. Schema of circulation to the orbit. Note that the ophthalmic artery is the sole vessel moving through the foramen. Evidence from several different sources suggests that blood may enter the orbit through branches of the maxillary and mandibular arteries of the external carotid. These would serve as a collateral supply to the ophthalmic artery system. There is no collateral system for the retinal artery. Thus, the retinal artery at point (1) is a true end artery for all of the retinal tissues; whereas the ophthalmic artery (2), except for the contributions referred to above, is an end artery for the intraorbital tissues considered as a whole.

retina suffice to induce irreversible changes; restoration of flow by collateral circulation after this time cannot restore function in any oxygen-dependent tissue.12,13

Diversion of blood among the several beds supplied by a single vessel is most obvious if these tissues have vastly differing blood flow demands, and if the need in one of the tissues varies widely from time to time. Limiting the arterial supply to a relatively uniform group of tissues with constant blood flow demands would tend to lower flow uniformly through all of the distal vascular beds.

Because of inadequate collaterals, partial occlusion at the point where the ophthalmic artery passes through the optic foramen would profoundly diminish the pressure in all the arteries within the orbit and increase the likelihood of diversions between the separate tissues. Branches of the ophthalmic artery supply even more varied tissues than those supplied by the brachial or the femoral arteries. The retina, with its high metabolic demands, calls for a very large blood flow per unit of tissue, but it is not clear whether this flow varies with activity. Resting extraocular muscles probably require less flow per unit of tissue than does the retina, but if such muscles are similar to skeletal muscle elsewhere, demand for blood should increase remarkably during and after contraction.14 The adipose pads and connective tissues within the orbit are very likely areas of relatively fixed flow. Finally, the ciliary body and other secreting organs may require variable amounts of blood flow. It follows that lowering pressure in the ophthalmic artery might seriously deplete blood supply to those tissues with the highest resistance and that intermittent vasodilatation in muscles during activity, for example, could
induce a corresponding intermittent ischemia of the "undilated" tissues. "Grayout" might accompany prolonged vigorous eye movements. In contrast, partial occlusion of the retinal artery could not significantly affect the diversion of blood flow between the retina and the extraocular muscles. Because it supplies a single tissue, partial occlusion of the retinal artery would uniformly diminish the flow through the retina. It might, however, divert the flow among various retinal regions if their resistances varied independently, or divert the flow between nutritional and shunt paths.

Besides diversion between tissues, blood flow may be shifted from the nutritional to the nonnutritional, or shunt, vessels. Thus, even when the total blood supply to a tissue is constant, shunt vessels can trade resistance with the parallel nutritional beds to vary the effective circulation.15 It has recently been suggested that a similar shift to the shunt circulation in the retina may deplete adjacent nutritional capillary circulation in diabetes.10 It is interesting to note that Barany17 reached the same conclusion about a shift to shunt circulation at the expense of nutrition to skin in diabetics. Perhaps because of the fact that the point of increased vascular resistance in diabetes is in small vessels beyond the point of entry of significant collaterals, the situation for diversion between the categories of vessels within the microcirculation is exaggerated in this disease.

Dilatation of resistance vessels under conditions of relative ischemia can compensate in part for the diversion. In skeletal muscle and skin, reactive hyperemia may lower the resistances to less than a tenth of normal, which implies the ability to maintain a constant perfusion in spite of significantly lowered arterial pressure. This system for self-regulation of tissue nutrition has been fairly well documented in several peripheral systems.18, 19 This potential for dilatation of a blood vessel by the local products of ischemia probably varies from tissue to tissue, so that extrapolation to tissues within the globe is dangerous.

REFERENCES