

**Vascular Problems in
Musculoskeletal Disorders
of the Limbs**

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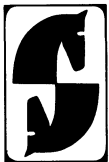
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Preface

That a close relationship exists between the specialties of peripheral vascular diseases and of orthopedic and general surgery has frequently been brought sharply into focus for both of us during many years of clinical experience in our respective fields of endeavor. Frequently, trauma to musculoskeletal structures has also been responsible for the production of a seriously compromised local blood flow, thus requiring a combined therapeutic approach to the solution of the problem. Improper utilization of appliances and conventional surgical procedures for common orthopedic conditions has on occasion likewise been followed by disastrous vascular complications. The fact that these possibilities exist in clinical practice has been the prime motivation for the development of this monograph.

The purpose of the volume is first to make readily available to the orthopedic or the general surgeon information that will allow him to determine whether a limb which he is treating is also suffering from an underlying impairment of arterial, venous, or lymphatic circulation. On the basis of such data, he should be in a better position to institute an appropriate and safe therapeutic program. Second, the subject matter should acquaint him with the necessary steps for early recognition of vascular complications of musculoskeletal disorders produced by trauma, with their differential diagnosis, and with their management. Finally, it should make him aware of the fact that a relatively large number of clinical entities possess both vascular and orthopedic components, and that it is essential to distinguish one from the other.

The monograph is divided into three parts. Section 1 consists of the gross and microscopic anatomy, physiology, pathophysiology, and pharmacology of the circulation in the skin, voluntary muscles, bones, and joints of the limbs. In Section 2 are described both the simple clinical tests of peripheral circulation capable of being carried out in the office or at the bedside and the more complicated laboratory procedures available in a large hospital. Section 3, the last and longest portion of the book, is devoted to discussions of disease states or entities. First, there is a description of clinical findings which are common to both circulatory and orthopedic conditions and then a presentation of vascular symptoms which mimic those of orthopedic origin. The second portion of Section 3 deals with such clinical entities as organic arterial diseases, both chronic and acute, and circulatory complications of musculoskeletal disorders of the limbs produced by trauma; the latter are categorized as injury to main blood vessels, factors responsible for venous thrombosis, clinical aspects of deep venous thrombosis, pulmonary embolism, postphlebitic syndrome, and fat embolism. Vascular and lymphatic tumors and malformation of the limbs are also considered in the volume, since these conditions frequently affect long bones and joints, as

well as soft tissues. In addition, the important subject of the possible serious vascular complications of therapeutic procedures utilized in orthopedic disorders is presented in detail, as well as the problems associated with minor or major amputations for the management of gangrene due to ischemia. Because of the current interest in limb replantation, this subject is also discussed. Finally, the medicolegal aspects of vascular difficulties as related to orthopedic disorders are considered.

To consolidate the contents of the volume and to make all data pertaining to a specific subject readily available to the reader, numerous cross references are found interspersed throughout the text. It is realized that such a practice may prove annoying; nevertheless it is believed preferable to repetition of material in different sections of the book. In order to facilitate location of the various items in the contents, each cross reference consists of a capital letter, which refers to a main heading in the chapter, followed by an Arabic number, which identifies a subheading preceded by the same number. The remainder of the cross references consists of the designation of the chapter in which the item is to be found.

If by perusing this monograph the orthopedic surgeon becomes more acutely aware of the role that vascular insufficiency may play in the practice of his specialty, then its purpose will have been achieved. It is hoped, too, that the volume will be of value to the emergency room specialist and to the general surgeon, who must take into consideration the local state of the circulation before undertaking any operative procedure on the limb. For the same reason, it should be useful to the podiatrist when he is contemplating a surgical or even a conservative approach to the treatment of abnormalities of the foot. Finally, it may be helpful to the physiatrist who must deal with the problem of rehabilitation of the injured patient, especially in the chronic stage of disability.

We wish to express our appreciation to Drs. Lee Lichtenberg, Svante O. Rolander, and Irwin Siegel for their painstaking examination of the manuscript and for the very constructive criticisms and suggestions which were then offered. Our thanks also go to Dr. Jack Stevens for making available to us the background material for the chapter on vascular and lymphatic tumors and malformations. We are grateful to Dr. Jiri Linhart for permission to reproduce the angiograms used as figures in the volume. Some of the other photographs have been obtained from the files of the Veterans Administration Hospital, Hines, Illinois, through the courtesy of Mr. Clark Moore. Mr. Abe Krieger of Springer-Verlag very ably and diligently supervised and participated in all the steps involved in the technical production of this volume, for which we are deeply grateful.

David I. Abramson
Donald S. Miller

Section 1

Vascular Beds in the Limbs

Chapter 1

Circulation to the Skin

In this and the subsequent three chapters are discussed the anatomy and physiology of the circulation in the different types of tissues comprising the limbs. Only those points are emphasized which have direct clinical application or are essential for the better understanding of altered structural or functional mechanisms responsible for pathologic changes in the vascular tree. The present chapter is devoted to the circulation to the skin.

A. General Considerations

1. Role of the Cutaneous Circulation

In addition to supplying the skin with oxygen and nutritive substances and removing metabolites arising from tissue activity, the cutaneous circulation has several other functions. Through its many vascular plexuses, capillary and venular beds, and other types of vessels, it acts as a reservoir when there is need for shunting blood to inactive tissues. Moreover, the extensive arteriovenous anastomoses have the capability of allowing large quantities of blood to circumvent the capillary bed and enter directly into the venous system, thus making possible relief from very high levels of blood pressure in the arterial tree. Because the skin is in contact with a wide range of environmental temperatures, the volume of blood that passes through it also plays a significant role in thermoregulation and preservation of a steady body temperature. In fact, under extreme con-

ditions of cold, local metabolic needs may be sacrificed for a long period of time in order to achieve the latter state. Finally, the cutaneous circulation is involved in a number of other homeostatic mechanisms, including the maintenance of the proper relationship between fluid volume and circulating blood volume.

2. Gross Morphologic Divisions of the Skin

The skin of the limbs is made up of a number of different layers. The most superficial one is the avascular epidermis, composed of squamous epithelium which receives its nutrition from the underlying capillaries located in the dermis. The latter structure consists of a thin superficial papillary layer and a deep reticular layer. In the dermis are found the hair follicles and the sweat and sebaceous glands—the appendages of the skin.

B. Anatomy of the Vascular Tree

The types of vascular networks in the skin are determined by the region of the body, the relationship of the skin to the underlying bone or fasciae, and the thickness of the panniculus adiposus. For example, in the fingers there is a very complex and abundant vascularity, beyond the degree necessary to supply nutrition to the comparatively thin epidermis and the small number of adnexal structures found in this site

4 Circulation to the Skin

[39]. Here the main function of the circulation is thermoregulation, with satisfaction of metabolic needs playing a secondary role.

1. Arterial and Arteriolar Beds

The vascular tree in the skin is derived from a network of perforating arteries arising in the subcutaneous tissue (Fig. 1.1). These vessels divide into an extensive anastomosing system (the deep arteriolar arcade) located between the deep reticular portion of the dermis and the underlying tissues. Generally vascular interconnections exist at all levels.

The deep arteriolar arcade gives off large numbers of arterioles which pass to sweat glands or hair follicles or supply the adjoining portion of the subcutaneous tissue. Others as-

cend through the various layers of the dermis, producing a “candelabrum” type of branching and eventually dividing into nutrient capillaries (Fig. 1.1). The deep arteriolar arcade is also the source of arterioles that spread upward to form a more superficial network (subpapillary arteriolar plexus), which is located in the upper layer of the dermis, below the epidermis (Fig. 1.1).

2. Arteriovenous Anastomoses (Shunts)

Arteriovenous anastomoses are highly organized, short channels, approximately $220\text{ }\mu\text{m}$ in diameter, which establish direct communication between the arterial and venous trees above the level of the capillary bed (Fig. 1.2). They arise from small arteries and end in small veins and are found in the stratum reticulare of the skin of the hands and feet, the greatest number being present in the nail bed of the finger and toe (as many as 500 per square centimeter). The fingertips, finger pad, palmar aspects of the fingers, sole of the foot, and thenar and hypothenar eminences of the hand contain somewhat fewer but still a large number of these structures.

The coiled, thick-walled afferent artery or arteriole, the connecting loop (arteriovenous anastomosis), the neuroreticular and vascular structures around the canal, and the efferent vein, collectively, are termed the glomus (Fig. 1.2B). Distal to this globular organ, the artery divides into smaller branches that ultimately terminate in the capillary bed.

The arteriovenous anastomosis possesses a small lumen (about $20\text{ }\mu\text{m}$ in diameter) and a thick muscular wall devoid of an internal elastic membrane. In the contractile layer are found the characteristic glomus cells, epithelioid in appearance. The arteriovenous anastomosis is enclosed in loose, finely fibrillar collagenous tissue containing a rich network of unmyelinated sympathetic and myelinated nerve filaments.

3. Capillary Bed

The capillaries in the skin are relatively few in number (16 to 65 per square millimeter [37],

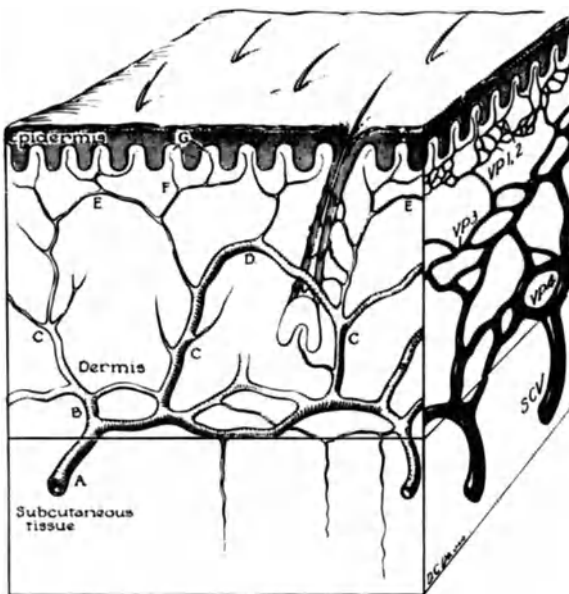


Fig. 1.1. Diagrammatic representation of the arterial and venous systems of the skin. A, Perforating artery; B, cutaneous plexus; C, arteriole (candelabra vessel); D and E, arched anastomoses—the superficial arcades form the subpapillary arteriolar plexus; F, terminal arteriole; G, arterial limb of capillary in a papilla. VP1 and VP2 form the subpapillary venous plexus. VP3 and VP4 form the deeper venous plexuses. SCV, Subcutaneous vein. From Moreci AP, Farber EM: In Abramson DI (ed): *Blood Vessels and Lymphatics*. New York, Academic Press, 1962. Reproduced with permission.

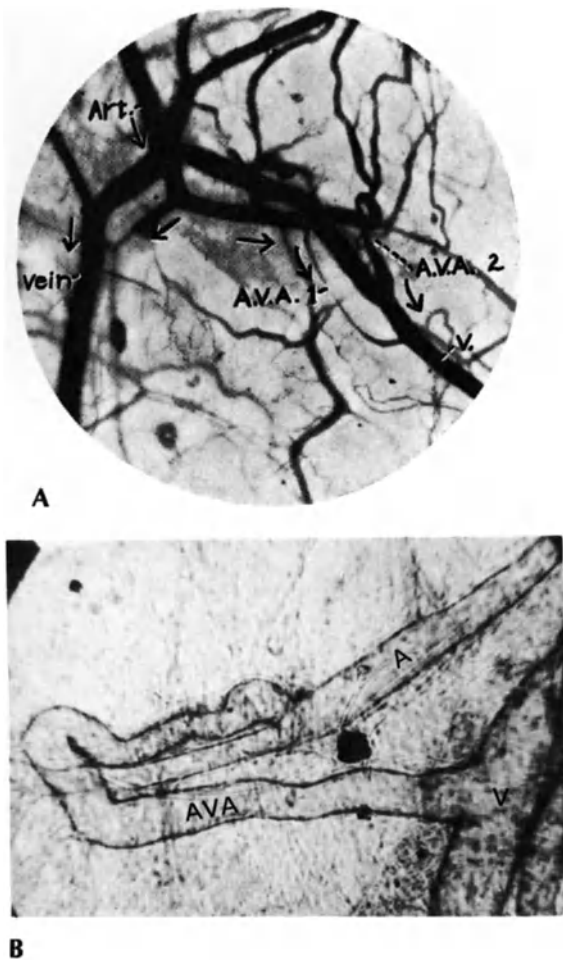


Fig. 1.2. Arteriovenous anastomoses. **A** Photomicrograph of a small area of living vessels in the rabbit's ear viewed through a stable preformed tissue chamber installed 1 month previously. Two arteriovenous anastomoses are seen, one straight (*A.V.A.1*) and one coiled (*A.V.A.2*), both arising from the same artery and emptying into the same vein (*V*). Arrows indicate direction of flow of blood in arteries. $\times 32$. From Clark ER, Clark EL: Observations on living arteriovenous anastomoses as seen in transparent chambers introduced into the rabbit's ear. *Am J Anat* 54:229, 1934. Reproduced with the permission of the American Journal of Anatomy. **B** Injected and cleared specimen obtained from the external ear of the rabbit. *AVA*, arteriovenous anastomosis arising from an artery (*A*) and emptying into a vein (*V*). The continuation of the artery subdivides (*left*), its branches eventually ending in a capillary bed. From Abramson DI: Pathophysiology of arteriovenous shunts in the extremities. *J Cardiovasc Surg* 7 (Suppl):217, 1966. Reproduced with the permission of the Journal of Cardiovascular Surgery.

as compared with 1000 to 2000 per square millimeter in underlying muscle [24]). They originate from a succession of arterioles and do not anastomose freely; instead they form separate loops supplying the dermis and the basal layer of the epidermis. At the base of the nail and dorsum of the finger, the loops are hairpin-shaped, consisting of a shorter, narrower limb, the arteriolar portion, and a thicker, larger limb, the venous portion; the two are joined by a short communicating segment (Fig. 1.3B and D). The capillary loops vary from 0.15 to 0.3 mm in length and, when dilated, are up to $10\ \mu\text{m}$ in diameter at the arteriolar end and up to $15\ \mu\text{m}$ at the venular end. There is an apparent relationship between the number of capillary loops and degree of development of the rete ridges; with age the latter structures tend to flatten and the capillary loops tend to become less in number and smaller in size. In places the capillaries are contorted and spiral, changes which have been interpreted as a means of preventing vessel rupture when the skin moves laterally [28].

4. Venular and Venous Beds

The cutaneous venules consist of four layers of vessels which run parallel to each other and to the surface of the skin and are found at different levels of the dermis, forming a candelabrum system of channels (Fig. 1.1). Those which drain the papillary loops merge to form the most superficial plexus located just below the papillae. The network beneath this one is in close association with the subpapillary arteriolar plexus. Blood from both venular beds (combined subpapillary venous plexus) (Fig. 1.3A and C) is collected into a third one which is located approximately in the middle portion of the dermis. The fourth and deepest venular network is situated between the dermis and the subcutaneous tissue, near the cutaneous arterial plexus (Fig. 1.1). It receives blood from the sweat glands and adipose tissue and empties into large subcutaneous veins and the deep venous system accompanying the arteries. There is marked looping of the venules in the different networks, thus allowing for mobility of the skin without rupture of these vessels.

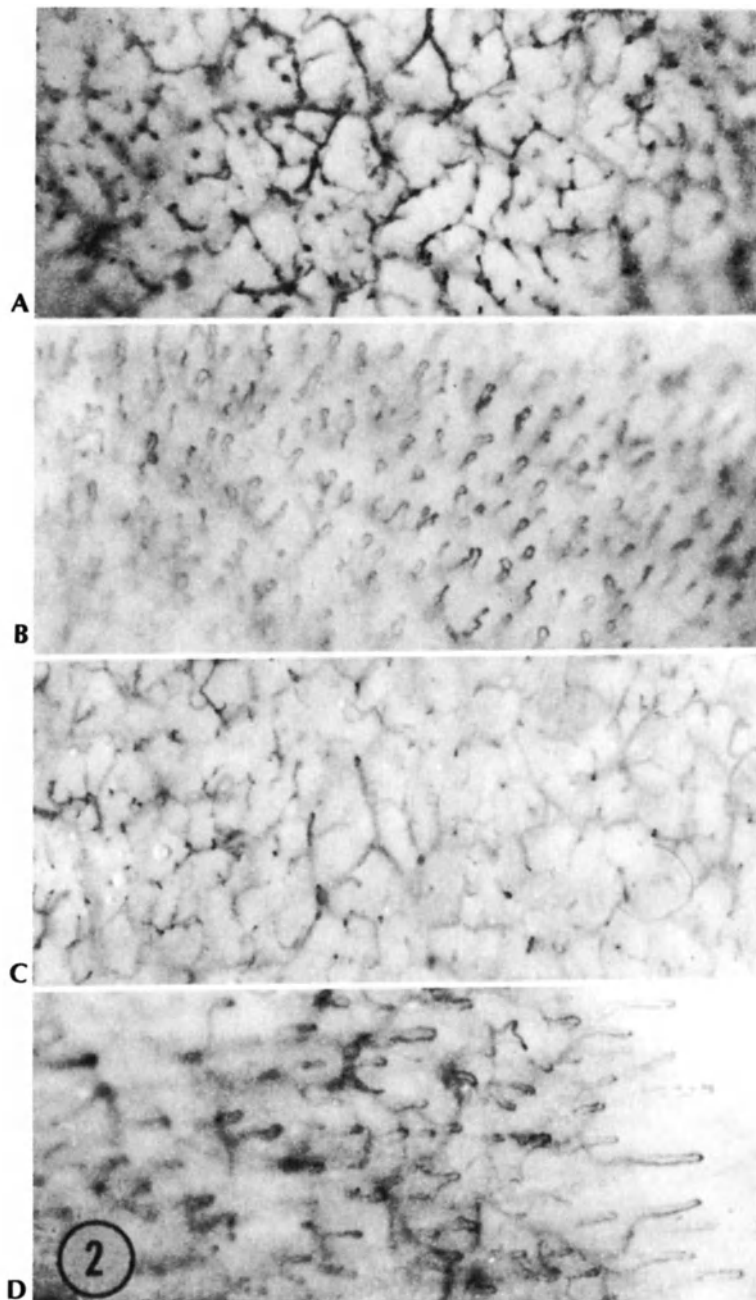


Fig. 1.3. Examination of cutaneous microcirculation in the human hand. **A** Capillaries and subpapillary venous plexus in skin of hand, as seen after removal of keratinized layers. **B** Normal capillary bed of dorsum of finger demonstrating capillary loops. Subpapillary venous plexus not well visualized. **C** Normal capillary bed of dorsum of hand. Subpapillary venous plexus clearly visualized. **D** Nail-fold capillaries of finger. Marked sludging of blood noted in end capillaries as indicated by deformity of normal smooth axial stream. From Davis MJ, Lawler JC: In Montagna W, Ellis RA (eds): *Advances in Biology of the Skin*. New York, Pergamon Press, 1961. Reproduced with permission.

5. Vascular Supply to Appendages

Hair follicles receive their blood supply from branches of the candelabrum system of arteries. From the branches arises an elaborate plexus of capillaries which surrounds the individual hair follicle (Fig. 1.1). In the lower third of the follicle the vessels run parallel to this structure, being interconnected by numerous

cross shunts [19] and running straight down to the core of the papilla.

The eccrine sweat glands receive their blood supply partly from the candelabrum system of arteries and partly from the cutaneous arterial plexus. Each gland is surrounded by capillary loops which follow the different contours of the tubule and give off branches that connect vessels that run along adjacent structures [19].

The blood supply to the apocrine sweat glands is from capillaries that have their origin in arterioles located at the junction of the hypodermis and dermis. The microcirculation forms plexuses of loops and intercommunicating branches and cross shunts around the tubules of the gland.

6. Innervation of Blood Vessels

From their origin in the vasomotor center in the medulla oblongata, the sympathetic preganglionic fibers pass down the intermediolateral cell columns of the spinal cord and leave the cord at intervals to make synapse in the paravertebral sympathetic ganglia with the postganglionic fibers. The latter run in somatic nerves to reach the peripheral blood vessels where they terminate in the alpha-receptor nerve endings in the vascular smooth-muscle cells (Fig. 1.4). Many alpha receptors are found in cutaneous vessels, whereas beta receptors are absent, this being the reverse of the situation present in muscle vessels.

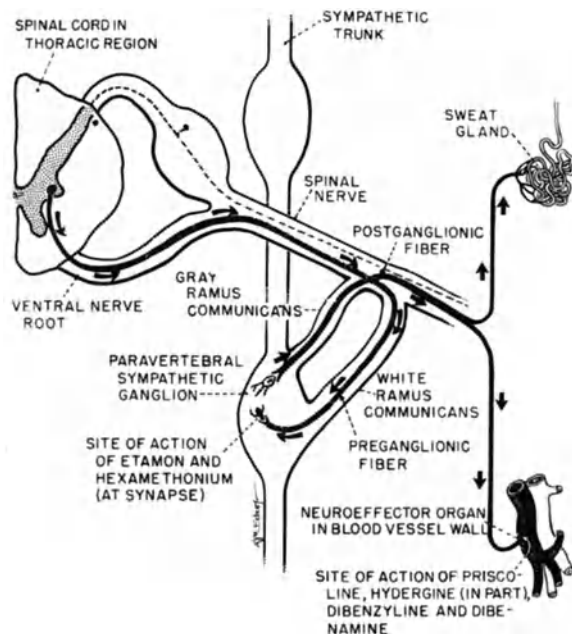


Fig. 1.4. Schematic representation of peripheral sympathetic pathways. From Abramson DI: Peripheral arterial vascular disorders. In Zimmerman LM, Levine R (eds): Physiologic Principles of Surgery. Philadelphia, Saunders, 1957. Reproduced with permission.

As already indicated, the arteriovenous anastomoses possess a rich innervation of sympathetic nerve fibrils. Although the latter enter the adventitia and smooth muscle cells forming the outer layers of the vessel walls, they do not appear to penetrate deeply into the centrally situated mass of epithelioid cells [30].

With regard to the sympathetic supply to venules and veins, the evidence is fragmentary, although the general impression is that these vessels are sparsely innervated by adrenergic fibers. This is of interest in view of the fact that veins have been noted to have rather active contraction and relaxation phases.

C. Physiology of the Vascular Tree

1. Laboratory Methods for the Study of Cutaneous Blood Flow

The cutaneous circulation in the limbs of man has been subjected to extensive physiologic study, due, in great part, to the fact that it is readily accessible to different methods of investigation, particularly in the case of the hand.

Microcirculation. The capillary circulation in the skin has generally been studied in the nail-folds of the fingers, using a capillary microscope (Fig. 1.3D). The vessels in these sites run parallel to the dorsal surface of the digit. In other portions of the limbs, it is necessary first to remove the keratin layer by blistering or by repeated applications of cellulose tape (Fig. 1.3).

Venous occlusion plethysmography. This method has been used in many experimental investigations, generally in the study of the hand which is made up primarily of skin if non-vascular tissues are disregarded. If the forearm (which contains a large quantity of muscle) is being investigated, it is necessary to utilize an equation derived from the average volume of skin in this segment of limb, as determined by dissection of cadavers, to obtain readings which represent the contribution solely of the cutaneous circulation [15].

2. Rate of Cutaneous Blood Flow

It is important at the outset to call attention to the fact that caution must be observed in any attempt to correlate total cutaneous blood flow measurements with the nutritional needs of the skin, since the vascular supply to this tissue also plays a very significant role in thermoregulation (see C-4, below). It has been estimated that as small an amount as 0.8 ml/min per 100 ml of tissue is sufficient to meet normal metabolic requirements of skin. Still, in the fingers, the resting circulation under physiologic conditions has been found to be as high as 15 to 40 ml and the rate may even rise to 90 ml with full dilatation [13]. Under the latter circumstances, most of the increase in blood flow is mediated through arteriovenous anastomoses and does not represent nutritional blood flow. In the forearm, resting cutaneous circulation under physiologic conditions ranges from 0 to 6 ml/min per 100 ml of skin [15]. Such wide fluctuations in local cutaneous circulation in different portions of the limbs and in different functional states reflect the multiple roles of cutaneous blood flow in physiologic processes of the body as a whole.

3. Nervous Regulation of the Cutaneous Circulation

In the skin the sympathetic nervous system plays a very important part in regulating blood flow, whereas inherent myogenic tone is poorly developed. Such a situation is probably related to the significant role that the cutaneous circulation plays in thermoregulation (see C-4, below).

Central control. Nervous regulation of the peripheral vessels resides in the vasomotor center in the reticular formation of the medulla oblongata where vasoconstrictor impulses originate (pressor areas). In addition, there are regions in which inhibitory impulses arise that exert influence on vasoconstrictor outflow (depressor areas). Very little evidence exists to indicate that there is a distinct and separate vasodilator center.

The rate of formation of vasoconstrictor impulses in the vasomotor center is modified by the action of higher centers in the subcortical

areas, the hypothalamus (temperature regulating center), and the cerebral cortex. An extensive autonomic representation is found in the latter structure, especially in its motor area, the orbital surface of the frontal lobe, the rhinencephalon, and the temporal lobe. As a result of a very complex arrangement of neuron pools supplying vascular circuits, a differentiated central vasomotor regulation is established which has been characterized as a multilevel control [29].

Vasoconstrictor nerves. Sympathetic vasoconstrictor activity is the most important mechanism available for rapid adjustment of blood flow through the cutaneous vascular bed. As already indicated (see B-2 and B-6, above), the arterioles and arteriovenous anastomoses in the skin are richly supplied by a network of sympathetic adrenergic fibers, stimulation of which causes vasoconstriction at the alpha-receptor sites (neuroeffector end organs). The actual mechanism initiating the response is the release of a neurotransmitter, norepinephrine, at the adrenergic receptor site. This hormone is rapidly formed and liberated, thus permitting a swift and sustained reaction to it. Only very small amounts of norepinephrine escape into the bloodstream by the slower process of diffusion. The rate of discharge of vasoconstrictor impulses is low, not exceeding 1 or 2 per second even under conditions of marked activation [20].

Vasomotor control is particularly marked in the distal portions of the limbs, the fingers and toes. Although there is no question that regulation of the arterioles and arteriovenous anastomoses in these sites is accomplished primarily through adrenergic nerves, there is some suggestive experimental evidence supporting the view that the digital arteriovenous anastomoses also possess a cholinergic innervation which is responsible for vasodilatation [23,27]. In the more proximal portions of the limb, vasomotor control over the cutaneous circulation is much less marked than in the distal segments.

Vasodilator nerves. Although it is generally agreed that vasodilatation in the cutaneous circulation is elicited primarily by inhibition of vasoconstrictor tone or by some locally induced autoregulatory mechanism, some data have

been presented in favor of the hypothesis that this state may also be produced actively through sympathetic cholinergic vasodilator nerves [18,34]. According to this concept, impulses passing over these structures stimulate gamma receptors through the production of acetylcholine. However, such a view has not been universally accepted because of conflicting evidence. The only conclusions that can be reached at present are that the functional activity of vasodilator nerves in the hand or foot under normal conditions has not been established [21,36] and that if such structures do exist, their physiologic significance must be very limited [8,35].

4. Role of Cutaneous Circulation in Thermoregulation

Of primary importance in the function of thermoregulation are the arteriovenous anastomoses, particularly those in the hands. When there is need for heat dissipation, these structures dilate and allow large quantities of blood to enter and flood the superficial veins without the need to traverse the cutaneous capillary bed, thus facilitating loss of body heat to the environment. When body heat must be conserved, as with exposure of a large surface area to cold, the arteriovenous anastomoses close entirely. Hence, all of the blood reaching the extremities must now pass through the minute vessels of the capillary bed which are also constricted by the same stimulus. As a consequence, the amount of blood entering the superficial veins is markedly reduced, with the great proportion of circulating blood volume being diverted to the internal organs where loss of heat is minimal. If exposure to cold is prolonged, the arteriovenous anastomoses and capillaries will eventually open intermittently, thus flooding the cutaneous venules with oxygenated blood and temporarily coloring the skin red (cold erythema). Subsequently cyanosis will intervene.

The marked influence that the sympathetic nervous system exerts on the arteriovenous anastomoses permits ready lability in the mechanism of dilatation and constriction of these vessels, in accordance with body requirements. In this function the arteriovenous anastomoses

supplement the action of the capillaries which are limited in their capacity to cope with extremes of environmental temperature because of their relative paucity in the skin.

5. Hormonal Control of the Cutaneous Circulation

Under normal conditions, blood-borne vasoconstrictor substances, like epinephrine, norepinephrine, and serotonin, are of negligible importance in regulating cutaneous blood flow, the vasomotor control being dominated by neural vasoconstriction via the peripheral sympathetic nervous system (see C-3, above). Only when there is a massive sympathetic activation do vasoconstrictor hormones play a role in reinforcing the direct action of sympathetic innervation [14].

Epinephrine causes marked blanching of the skin, due to strong constriction of the cutaneous blood vessels, including the arterioles, precapillary sphincters, and muscular venules; the evidence is lacking for a similar response in the capillary bed.

Norepinephrine also produces vasoconstriction of muscle-containing blood vessels in the skin, but the effect is not as marked as with epinephrine. The action of this hormone, as in the case of epinephrine, is through stimulation of alpha (constrictor) receptors in the blood vessel wall.

In regard to serotonin (5-hydroxytryptamine), the evidence is not as clear-cut. However, most of the experimental work appears to favor the view that this agent produces constriction of resistance vessels and dilatation of the microcirculation in the skin [33]. It may also have a direct vasoconstrictor effect on cutaneous and subcutaneous veins [16,26,31]. Commonly, with intradermal injection of serotonin, erythema and a flare result.

6. Vascular Changes Produced by Physical Agents

Direct heat. The topical application of such a stimulus causes a marked increase in cutaneous blood flow [6,7]. The vasodilatation is due to a very potent direct effect on cutaneous ar-

teries and arterioles and is not related to inhibition of vasomotor tone, the same type of response also being noted in the sympathectomized limb [2]. At the same time, there is a significant rise in tissue temperature (Fig. 2.2A) [6] and a resulting increase in metabolic needs. Under normal conditions, the latter is readily satisfied through the associated marked augmentation in blood flow, which also acts as an efficient cooling system for the removal of heat from the exposed area. As a consequence, the augmentation in tissue temperature and metabolic needs is tempered and reduced.

The situation in the presence of occlusive arterial disease is entirely different. Heat is incapable of effectively dilating vessels that are organically partially occluded and hence the increase in local blood flow produced by this agent is much smaller than normal. As a result, the efficiency of the cooling mechanism supplied by the movement of blood through the tissues is impaired. Consequently, the tissue temperature will begin to approximate the level of the applied heat, thus causing a very great rise in metabolic needs of the exposed tissues. Since under the circumstances no effective means are available to satisfy such extreme requirements, necrosis of skin and underlying structures will inevitably occur. It is for this reason that no form of physical therapeutic procedure which develops heat in the tissues (e.g., short-wave diathermy, infrared lamp, ultrasound, ultraviolet light, topical wet or dry heat, paraffin bath, hot packs, heating pad) should ever be prescribed without first ascertaining that the local arterial circulation is normal.

Indirect heating. The application of heat to distant portions of the body to produce reflex or indirect vasodilatation in the hands or feet is an effective means of increasing local cutaneous blood flow without any of the risks associated with direct heating (see above). However, the vasodilator response, which is due to inhibition of vasomotor tonus, is never as great as that initiated by the direct application of the agent [1].

The mechanism responsible for the increase in cutaneous blood flow is as follows: The temperature of the blood passing through the

heated portions of the body is raised, with the result that after 30 min of exposure, the body temperature is also elevated, provided heat is prevented from being lost to the environment by covering the subject with blankets. The heated blood, on perfusing through the temperature regulating center in the hypothalamus, stimulates this structure and, as a result, impulses originating there pass down to the vasomotor center where they act to inhibit discharges of vasoconstrictor impulses. Such a situation permits the cutaneous arterioles, normally under the control of the vasomotor center, to dilate passively, thus increasing blood flow to the skin, particularly of the fingers and toes.

Since there is only a slight elevation in tissue temperature with indirect vasodilatation (resulting from the more rapid blood flow through the skin) [3], the rise in metabolic needs is minimal. Hence, the procedure is entirely innocuous, even in the presence of a marked compromise of the local arterial circulation. For example, if the vessels are unable to dilate on removal of vasomotor tone because of organic disease, then even the minimal rise in skin temperature will not occur because of the resulting small increase in cutaneous blood flow, and so there will be no change in metabolic needs.

Electric modalities. Short-wave diathermy has very little vasodilating effect on cutaneous circulation, its greatest response being on underlying tissues [5]. However, the infrared lamp appears to exert a moderate vasodilating action on the skin vessels. Ultrasound is ineffective in this regard [4].

Direct cold. Topical application of this agent produces marked vasoconstriction of the cutaneous circulation. The response is due to a direct effect on the vessels themselves, particularly the arterioles, without the mediation of sympathetic vasoconstrictor nerves.

7. Vascular Responses to Drugs

The cutaneous circulation is altered by a large number of vasodilator or vasoconstrictor drugs.

Vasodilator agents. Augmentation of cutaneous circulation can be achieved through several different mechanisms. Normal or abnormal vasomotor tone can be eliminated by means of sympathetic blocking agents which act by competitive inhibition at the alpha-receptor endings (neuroeffector junctions) in the blood vessel wall. Among such drugs are tolazoline (Priscoline), phentolamine (Regitine), derivatives of ergotoxine (Hydergine), and phenoxylbenzamine hydrochloride (Dibenzyline). Reserpine (Serpasil) is of value in antagonizing the effects of circulating epinephrine and norepinephrine and in impairing catecholamine retention in tissues, with subsequent loss in physiologic effectiveness by degradation [25]. The drug also appears to abolish the ability of the sympathetic nerves to bind norepinephrine, followed by inactivation of the latter by oxidative deamination. Ganglionic blocking agents, like tetraethylammonium chloride, act temporarily to destroy the continuity of the sympathetic nervous system by blocking vasoconstrictor impulses at the level of the paravertebral sympathetic ganglia. Whiskey and other alcoholic beverages cause cutaneous vasodilatation by depressing the rate of formation of vasoconstrictor impulses in the vasomotor center in the medulla.

Another group of drugs which causes vasodilatation in the skin is the myovascular relaxants, agents which have a direct paralyzing action on the smooth muscle of the cutaneous blood vessels. In this category are oral nicotinic acid, oral cyclophosphamide (Cyclophosphol), 2 percent nitroglycerin ointment (Nitrol ointment) by topical application, histamine hydrochloride by ion transfer, papaverine hydrochloride by intraarterial injection, and procaine hydrochloride by direct contact with the vessel.

8. Effect of Sympathetic Denervation on Cutaneous Blood Flow

Removal of sympathetic control over normal cutaneous blood vessels, as by sympathetic blocking agents, paravertebral or stellate ganglionic block, peripheral nerve block, or sympathectomy, immediately produces signs of an increase in blood flow through the skin. These consist of a significant rise in cutaneous tem-

perature, rubor of the skin, and bounding pulses, associated with anhidrosis. Blood pressure in the small cutaneous vessels increases.

The changes are most marked in the distal portion of the limbs, the digits, a finding which can be correlated with the relative anatomic distribution of sympathetic vasomotor nerve fibers. The intensity of the response becomes less and less as the proximal portion of the limb is approached. Even in the hand and foot, the rise in cutaneous temperature is almost limited to the digits, with changes elsewhere being of much smaller magnitude. Removal of sympathetic control has been reported to have a paradoxical effect: a decrease in tone of the arterioles and an increase in tone of the capillaries [12]. There is also some suggestive evidence that marked vasodilatation occurs in the arteriovenous anastomoses [32], which could explain the finding that the greatest increase in cutaneous temperature following sympathectomy occurs in the digits, the site of the highest concentration of these vascular structures.

Considerable experimental evidence exists to indicate that the augmentation of cutaneous circulation produced by sympathectomy is transient [9,11,17,22,38]. The return of blood flow to nearly preoperative levels occurs several weeks after surgery. The response appears to be due to reestablishment of vascular tone, although the explanation for such a phenomenon is not clear [9].

D. Pathology of the Vascular Tree

Because of its location, the cutaneous circulation is affected by external factors (such as extremes of temperature, exposure to roentgen rays and ultraviolet light, physical trauma, and chemical injury) to a much greater degree than are similar vessels in internal organs or even in the subcutaneous tissue. As a result, pathologic changes are not uncommon in this vascular bed. Among other abnormalities or states affecting the cutaneous circulation are hereditary defects, systemic disorders, and alterations in vasomotor control. For example, in severe Raynaud's disease, most of the capillaries ap-

pear enlarged. In schizophrenia and neurocirculatory asthenia, they may be reduced in number, as well as demonstrating irregularities in size and shape. Changes in capillary structure may also be seen in such disorders as scleroderma and acrocyanosis, the alterations taking the form of unusually shaped loops, minute aneurysms, or saccular enlargements. Also, abnormal periodicity of flow may be noted in the microcirculation. In polycythemia and hyperthyroidism, the number of open capillary loops are significantly increased, individual vessels are more dilated than normally, and the total cross section of capillary bed is enlarged. In thromboangiitis obliterans and arthritis, the capillaries are fairly normal in caliber and tonus [12]. (For discussion of other specific disorders in which there are pathologic changes in the cutaneous circulation, see pp. 116, 130, 152, and 320.)

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