Venodynamics in healthy subjects and in patients with venous dysfunction

Einar Stranden
Department of Vascular Diagnosis and Research, Surgical Clinic, Aker University Hospital
Oslo, Norway. einar.stranden@ioks.uio.no

SUMMARY
The idea of extremity vein pumps, and centripedal vein blood flow, was put forward by William Harvey in 1628. Since that time, numerous studies have established the role of the venous pumping system and the venous hemodynamics in maintaining normal microcirculation, as well as the involvement in venous dysfunction.

The common pathway leading to venous ulceration in the lower limbs includes ambulatory venous hypertension, caused by valvular dysfunction and thrombosis of segments of the deep venous system (1-3). Precisely how this hypertension leads to ulceration is unclear; several studies indicate that increased venous pressure disturbs normal function of the microcirculation and interstitium, including a local inflammation, which in turn causes venous ulceration (4-11). This presentation focuses on physiological aspects of the venous circulation in normal limbs and in those with venous dysfunction.

Flow through collapsible tubes

Veins can be regarded as thin-walled, easily collapsible tubes. The volume of a vein varies considerably due to the influence of internal and external pressure, hormones, vasoactive agens, temperature and nerve activity (12). It is, however, a misconception that veins are more distensible than arteries. This is illustrated by volume-pressure relationships, where initial filling of veins is achieved with small increase in pressure. In this phase the cross-section of the veins changes from ellipsoid to circular shape, without concomitant stretching of the vein wall (13). During the second phase the elements of the vessel's wall are stretched. The steepness of the volume-pressure curve reflects the elastic properties of the venous wall. In the stretching phase, the distensibility of veins is similar to that of arteries (13-15).

Flow through thin-walled, easily collapsible veins depends to a larger extent than in arteries on the level of external pressure. The venous pressure at which collapse occurs, the *tube pressure*, depends on external pressure and passive and active forces in the tube wall (16) (Fig. 1). This pressure is normally approximately equal to the external pressure in veins. The pressure within a vertical tube is higher at the bottom than at the top because of gravity. Accordingly, a higher external pressure is required to close the lumen near the bottom of the tube. The veins in the lower extremity may be regarded as a series of collapsible tubes, along which the effective tube pressure rises and falls because of changes in posture, the venous valves, and changes in external pressure due to muscular activity.

In the upright posture the venous blood pressure near the heart is close to zero. In a motionless upright posture, the venous blood pressure at the ankle rises to about 70-90 mmHg, distending the veins. This increased venous pressure would cause severe venous distension and transcapillary filtration if compensatory mechanisms were lacking. In healthy subjects this is prevented by the venous pumps.

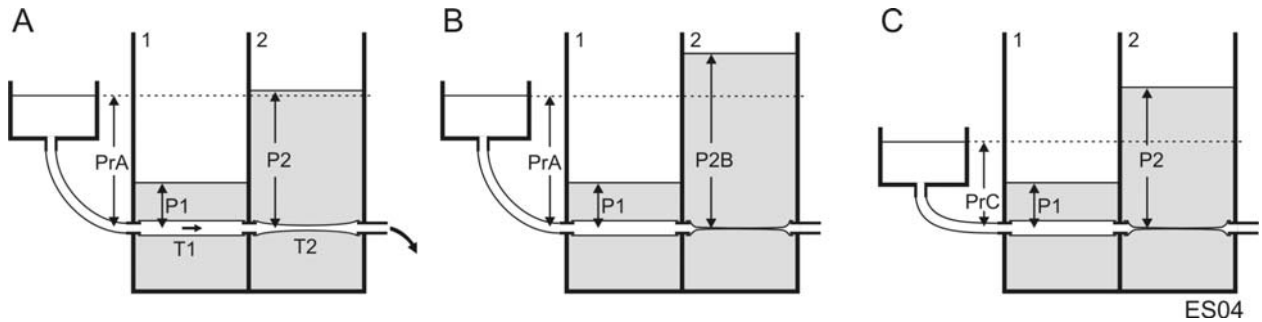

Fig. 1. *Schematic illustration of the effect of variation in internal and external hydrostatic pressures on collapsible tubes (T1 and T2) coupled in series through two chambers (1 and 2). Different fluid levels in the chambers exert different external hydrostatic pressures (P1, P2 and P2B) upon the tubes. At low fluid velocities the force distending the tubes is PrA in example A and B, PrC in example C. These pressures are high enough to withstand the external pressures in chamber 1 to keep the tubes open. In chamber 2 of example A the tube remains open, although the external pressure P2 is slightly higher than the distending pressure PrA. This is possible because of elastic properties of the vein wall which restrict change in the shape of the cross section. This restrictive force is higher in arteries than in thin-walled veins. Collapse of the tube occurs if the external pressure increases above a critical level (as in example B) or if the distending pressure decreases (as in example C). Clinical analogies to these examples are the application of elastic stockings or pressure cuffs, and the development of compartment syndrome (examples A to B), and the change in posture from erect to supine (examples A to C).*

The vascular driving-force

The difference in hydrostatic pressure is often referred to as the driving-force propulsing blood in the vascular bed. This is only partially true, when applied to restricted areas. The true driving-force is not a difference in *pressure*, but a difference in *total fluid energy* (17). The total fluid energy (E) is the sum of three terms: Pressure potential energy (P) created by the pumping heart, gravitational potential energy (ρgh) and kinetic energy ($\frac{1}{2}\rho v^2$), where ρ is the density of the fluid, g is the acceleration due to gravity, h is the height of the fluid column above the point of interest and v is the velocity of the fluid.

In resting-condition the kinetic component in the vascular bed is usually small compared to pressure energy, equivalent to only a few mmHg. Since the kinetic term is proportional to the square of the velocity, it may become significant when the fluid velocity is increased, for instance in the jet of venous blood ejected from a working calf muscle. Therefore, in a short period of time at the end of muscle contraction, blood may even flow *against* a pressure gradient. When velocity decreases during muscular relaxation, the kinetic energy component is reconverted into pressure energy, which again conforms to the notion of being the force behind venous flow.

The venous pumps in the lower limb

In the upright position a significant amount of blood is translocated to the lower extremity veins. During quiet standing, the muscles in the lower extremity contract and relax rhythmically, causing a swaying motion of the body. During muscular contraction blood is squeezed in proximal direction, and the veins are refilled during the relaxation phase. This cyclic muscular action and the venous valves form a powerful pumping system aiding the venous return to the heart (18). The return of blood from the extremity does not totally depend upon properly functioning pumps; cardiac activity alone is sufficient to maintain return flow (vis a tergo blood flow). The pump system is, however, of vital importance to preserve the integrity of the microcirculation, by reducing distal capillary pressure when standing (13).

Pumping occurs in all veins containing valves and is subject to oscillating surrounding pressure. Even without functioning venous valves, leg motion, by virtue of venous compression, promotes venous return (13). The venous pumping system may be divided into three portions with different working mechanisms (Fig. 2):

1. The muscle pumps
2. The distal calf ("piston") pump
3. The foot pump

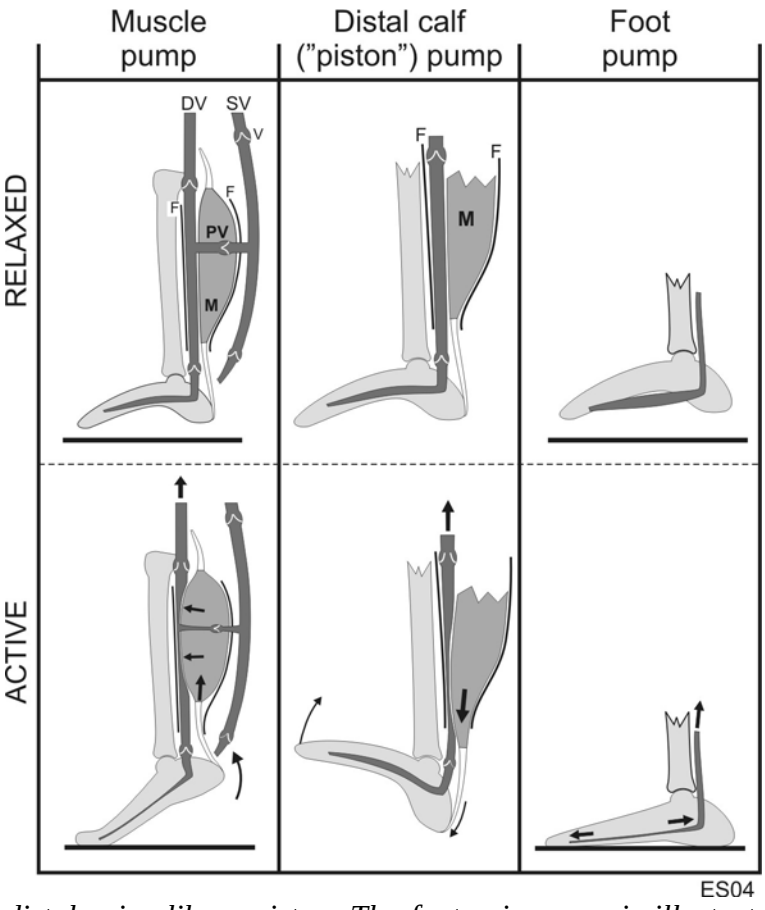

Fig. 2. *Schematic illustration of the venous pump systems of the foot and calf in relaxed and active state. The muscle pump unit consists of muscles (M) ensheathed by a common fascia (F) and veins within the same compartment. Contraction of the calf muscles (muscle systole), as in plantar flexion of the ankle joint during walking (below), expels blood into the proximal collecting vein. During relaxation (muscle diastole, above) the blood is drained from the superficial veins (SV) into the deep veins (DV) in addition to the arterial inflow, making the pump ready for the subsequent ejection. V: venous valve. The distal calf ("piston") pump is indicated in the middle. On dorsiflexion of the ankle (passive or active), the bulk of the calf muscle (M) descends within the fascial sheath (F), and expels blood in the distal veins like a piston. The foot vein pump is illustrated to the right. The plantar veins are connected like a bow-string from the base of the fourth metatarsal in front to the medial malleolus. On weight-bearing the tarso-metatarsal joints are extended and the tarsal arch is flattened. Thus the veins are stretched, causing them to eject their content of blood.*

The muscle pumps

The pump unit consists of muscles ensheathed by a common fascia, which is drained by a set of densely-valved intra- and inter-muscular veins. These in turn empty into more sparsely valved proximal veins (19). The leg contains four muscular compartments: The anterior, lateral, deep posterior and superficial posterior, all drained by their respective veins.

Muscle contraction is the main activator of muscle pumps (20-23), but passive stretching may also raise intramuscular pressure and promote pumping. Baumann et al. (24) recorded pressures of >100 mmHg in the tibial anterior muscle during contraction and 35 mmHg on passive stretching.

Contraction of the calf muscles initiates a rise in pressure in all veins of the lower limb (indicated in figure 5 below). The increase is most pronounced within muscle veins, three times higher than in superficial veins. In the proximal collecting (popliteal) vein the pressure increase is insignificant. During muscle contraction (systole) the greatly increased pressure difference between deep calf veins and the popliteal vein causes rapid flush of blood from the calf to the thigh (Fig. 2). Retrograde flow is prevented by competent venous valves. On subsequent muscle relaxation (diastole) venous pressure falls below the pressure at rest. The fall is greatest in the deep veins, less in the superficial veins and insignificant in the popliteal vein. In this phase perforator veins allow flow from the superficial to the deep veins, whereas competent valves prevent backflow from the popliteal to the deep calf veins.

The calf pump is probably the most important muscle pump. However, also the thigh pumps (quadriceps muscle pump, sartorius muscle pump, the pump of the hamstring muscles) and the popliteal vein pump (25) play a part in the centrally directed propulsion of blood.

The distal calf ("piston") pump

In contrast to conventional descriptions, there are two pumping systems in the calf, a proximal and a distal (18). The distal one is activated on dorsiflexion of the ankle (Fig. 2), when the calf muscles are stretched and their distal part descends within the fascial sheath. This movement acts like a piston which expels venous blood in proximal direction. The pump mechanism has been documented by ultrasound Doppler measurement of venous blood flow (18), and is supported by compartment pressure measurements (26).

The foot pump

The significance of a pumping system within the foot has often been overlooked, although first postulated by Le Dentu in 1867 (27). Gardner and Fox (18,28,29) used video-phlebographic technique and ultrasound Doppler measurement to demonstrate a potent pump mechanism in the deep plantar veins. This pumping action does not depend on muscular movements, as it functions even in paralysed limbs (18). Furthermore, the muscles in the sole of the foot are in a relaxed state during weight-bearing (30,31). This venous pump does not depend on direct pressure on the plantar veins, since weight-bearing involves almost exclusively the ball of the toes, heel and lateral aspect of the plantar surface (32). The pumping mechanism has been explained as follows. The plantar veins are connected like a bow-string between the base of the fourth metatarsal and the medial malleolus. On weight-bearing, the tarso-metatarsal joints are extended and the tarsal arch is flattened. Thus the veins are stretched, causing them to eject their content of blood (Fig. 2). The pump is also activated on weight-bearing of the forefoot alone, when the foot is acting like a lever (18) (Fig. 2, left portion).

The pumps acting together

During normal walking the three vein-pumping systems are synchronised to form a complete network of serial and parallel pumps aiding the return of blood towards the heart. The mechanism may be summarised as:

1. Before weight-bearing the ankle is dorsi-flexed, emptying both anterior muscle compartment (muscle pump) and the distal calf ("piston" pump).
2. At weight-bearing the foot veins are emptied (foot pump).
3. The plantar flexion of the foot to ensure forward locomotion activates the proximal calf pump of the posterior muscles (muscle pump).

Edema reduction with venous pumping

The venous pump systems normally reduces dorsal foot vein pressure from approximately 70-90 mmHg at the passive upright position to below 30 mmHg during ambulation, with concomitant reduction in transcapillary fluid filtration. To assess the effectiveness of the venous pump system, factory workers in an electronic assembly plant were studied (33). Their tasks required a fixed height worktable and a footrest. Complaints by the operators of swellings and paresthesia of feet and ankles were followed up by examination using water displacement volumetry. Five hours of operation at the workstation led to a mean volume increase of the foot and leg of 3.8 % (n = 19). Corresponding measures of interstitial fluid pressure using the "wick-in-needle" technique, indicated a mean increase in pressure of 1.6 mmHg. The results produced a positively correlation between changes in volume and change in interstitial fluid pressure ($r=58$, $p<0.005$).

When redesigning the workstation a dynamic foot-rest was developed, incorporating a pivot which allowed "treadle" action to be performed by the operator on a regular basis (Fig. 3). Such movements activated the venous pump system, as indicated by reduction in saphenous vein pressure and calf volume (the left portion of the curves in figure 3). Interestingly, we found that a single forward flexion of the foot generated similar pressure and volume reduction profiles as series of repeated manoeuvres. These findings were applied in the redesign, and very quickly the operators learned to use the foot-rests regularly. The beneficial effect on transcapillary fluid balance by the dynamic foot-rest is indicated in figure 4, including calf volume changes during one hour with static (top) and dynamic foot-rest. The former produced a calf volume increase of about 1 %, whereas the calf volume *decreased* 1 % when using the dynamic foot-rest. The corresponding values for all subjects in the study were 0.8 % volume increase per hour for static, and 0.5 % volume reduction per hour for dynamic foot-rest, respectively.

When using the dynamic foot-rest, all subjects reported relief of discomfort, swelling and pain, demonstrating the potential of the venous pumps in restoring normal transcapillary fluid balance in a sitting posture.

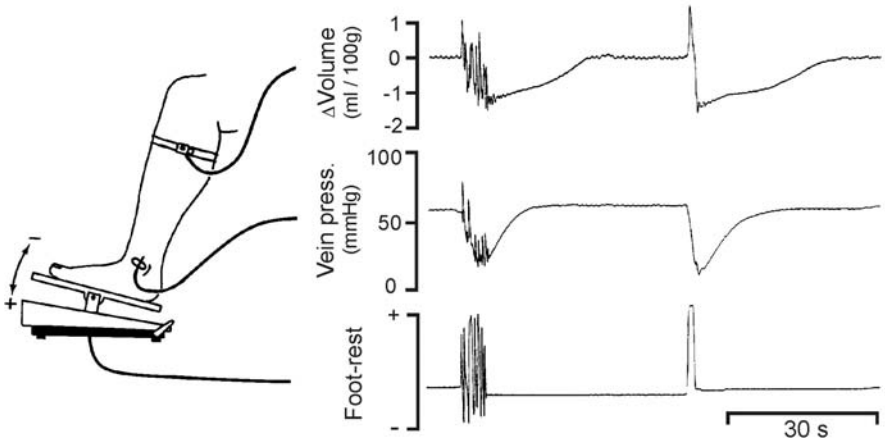

Fig. 3. *Recording of calf volume changes (ΔVolume), long saphenous vein pressure (vein press.) and "treadle" activity of a dynamic foot-rest developed for the study. Dorsi-plantar flexion of the ankle joint activated the venous pumping system, reducing both vein pressure and calf volume. A single forward flexion of the foot (right portion of the curves) was as efficient in pressure/volume reduction as repeated manoeuvres (left portion of the curves).*

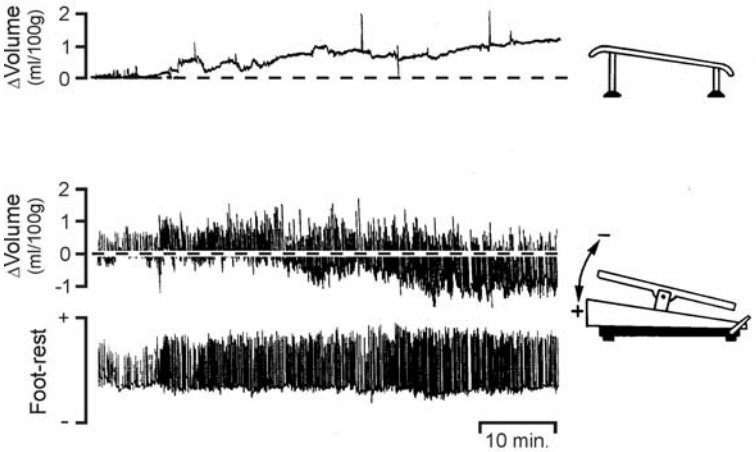

Fig. 4. *Calf volume changes (ΔVolume) during one hour chair-sitting in a factory worker with different level of venous pump activity using a static (top) and a dynamic foot-rest. The activity of the leg is indicated by a motion transducer connected to the foot-rest (bottom). In the relatively motionless posture the calf volume increased by about 1 %, whereas the calf volume decreased by the same amount with the foot-rest permitting leg muscle activity.*

Venodynamics of the lower limb

The venous system in the lower limb is composed of a subcutaneous superficial system, a deep system within the muscular fasciae and connecting perforating veins. Dysfunction, mainly of the valves, may occur in each system and in combination. The great variability in venous anatomy and function makes pathophysiological understanding rather complex. The following description of four clinical conditions is therefore simplified. The pressure- and flow-curves of the examples are a synthesis of numerous published studies, e.g. studies of venous pressure by Arnoldi (34-39), the studies of pressure and flow by Bjordal (40-45), and non-invasive investigations (46, 47).

Normal venodynamics

In the upright position, the hydrostatic vascular pressure is greatly increased in the lower part of the body. The increase is similar in arteries and veins, and should *per se* have little effect on the overall blood-flow through the lower limb. However, the very potent veno-arteriolar reflex initiated by distension of veins, at transmural pressures above 25 mmHg, causes arteriolar vasoconstriction which reduces blood flow in the dependent limb by approximately 50% (48-50).

In passive dependent legs, the pressures in all veins at the same height are equal, and are approximately equal to (slightly higher than) the hydrostatic fluid pressure in a column of blood from the point of measurement to the level of the heart (17). In this state, phlebography indicates that blood returns to the heart through both deep and superficial veins (19).

Muscle contraction (systole) at weight-bearing is accompanied by a rise in pressure in all veins of the limb (figure 5). Within the muscular compartment the increase is largest, typically 60-70 mmHg, three times higher than the rise in superficial veins. During systole the muscle contraction may cause venous outflow obstruction, further enhancing deep systolic vein pressure. In extreme cases the pressure is raised by more than 200 mmHg in a fraction of a second (19). The systolic venous pressure increase in the collecting conduits is smaller (appr. 20 mmHg, popliteal vein), and the resulting pressure gradient rushes blood from calf to thigh. Competent valves prevent distal flow or outward through the perforators. In addition, the higher deep venous pressure does not allow inward flow through the perforating veins during systole.

During muscle relaxation (diastole) the pressure falls below that at rest, especially in the deep veins (Fig. 5), ensuing an inward flow through the perforating veins. In healthy subjects patent

vein valves prevent flow in distal direction in both deep and superficial veins.

In repeated muscle contractions, as in normal walking, the systolic pressures in the deep and superficial veins will gradually fall and fluctuate at levels considerably below the pressures during a single contraction (Fig. 5). The superficial venous pressure in the ankle region during walking is typically 30 mmHg and is referred to as the ambulatory venous pressure (AVP).

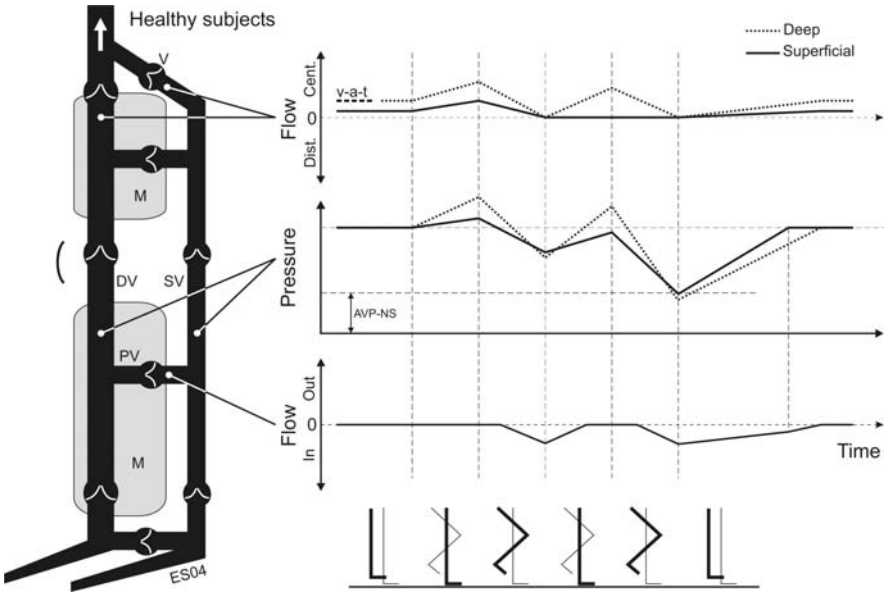

Fig. 5. *Schematic representation of normal anatomy and dynamics of lower extremity veins. The simplified venous system consists of superficial veins (SV), deep veins (DV) within muscular compartments (M) of the calf and thigh, and perforating veins (PV). A number of venous valves (V) ensure unidirectional flow of blood in central (cent.) direction in deep and superficial veins, and inward direction in the perforating veins. The diagram to the right depicts idealized pressure and flow characteristics of different areas of the veins during steady state at passive dependency (the leftmost walking-phase symbol) and two subsequent walking cycles - during weight-bearing (muscle systole) and elevation of the leg (muscle diastole). The solid line indicates the extremity under description. In a passive relaxed state the blood is forced almost solely through the deep system by the pumping action of the heart, often referred to as the* ***vis a tergo*** *(v-a-t) blood flow. AVP-NS is the normal ambulatory venous pressure in superficial veins.*

Superficial and perforator dysfunction

Relatively few patients referred to hospital have dysfunction of superficial veins combined with normal valvular function in the perforating veins. In this group the calf vein pumps are normal and ambulatory venous pressure in the deep veins at the ankle is low, which explains the absence of oedema and trophic changes in the skin (19).

Most patients with venous dysfunction have incompetent valves in both superficial and perforator veins. This causes a significant reflux in the superficial vein trunk and a smaller reduction in superficial venous pressure than normal (40), often referred to as "ambulatory venous hypertension". Although the venous pumps may be normal, the pressure in the deep veins is rapidly restored to the blood column pressure upon standing, because of backfill from the superficial veins (Fig. 6). The clinical picture is varicose veins and leg oedema, often in combination with trophical changes which sometimes develop. The more extensive and the more distal the venous reflux, the greater the probability of ulcer formation (51, 52).

In steady state at passive dependency blood flows primarily through the deep veins (40), and the pressure in the veins corresponds, as in healthy subjects, to the hydrostatic pressure from the

blood column to the heart. Consequently, the pressure at rest is not affected by valvular dysfunction. Weight-bearing with muscular contraction causes a steep rise in deep venous pressure, as in healthy subjects. The increase in superficial venous pressure is considerably higher than normal, due to by the extensive retrograde flow from the deep venous system through incompetent dilated perforating veins in muscle systole (42).

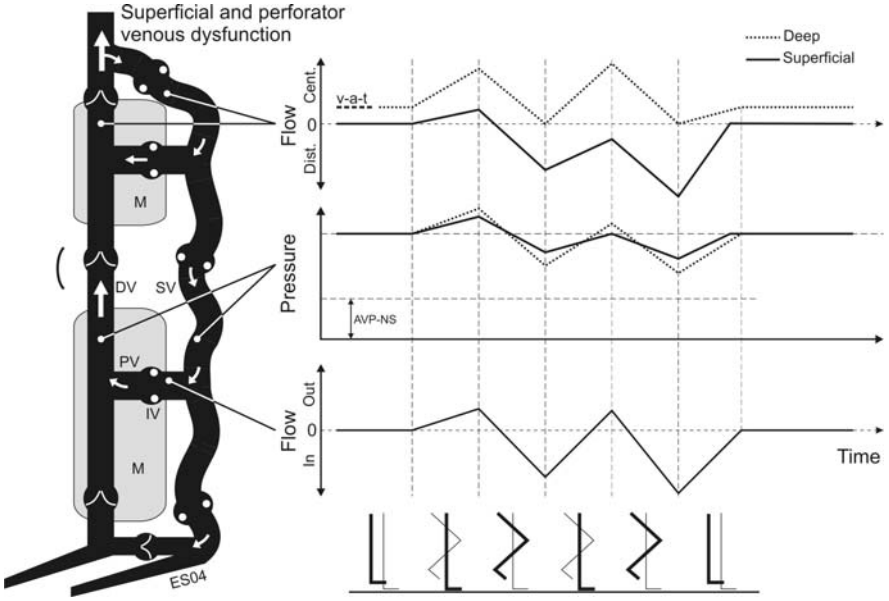

Fig. 6. *Schematic representation of anatomy and venodynamics of lower extremity veins in patients with superficial and perforator venous dysfunction. The most striking difference between healthy subjects and patients with incompetent perforating veins only is the distal (dist.) blood flow in the superficial veins (SV). This retrograde flow is in the order of 300 ml/min. during normal walking (40), causing net inward blood flow through the perforating veins. However, during ambulation there is oscillating flow in incompetent perforators, outward during muscle contraction and inward at muscle relaxation. Furthermore, the state is characterized by less reduction in venous pressure in superficial veins during walking, often referred to as "ambulatory venous hypertension". Annotations are as in figure 5.*

During relaxation the pressure in the muscular deep veins falls abruptly, and to a larger extent than in popliteal and superficial veins. This causes an inward movement of flow through the perforating veins, whereas reflux from the popliteal vein is prevented by valves. The absence of competent valves in the superficial system allows retrograde flow, most often through the sapheno-femoral junction. Bjordal (40) quantified this reflux in the superficial main trunk during normal walking as an average of 300 ml/min., and thus verified the hypothesis of "a private circulation" as suggested by Trendelenburg (53). According to his finding a large fraction of the blood from the deep venous trunk is "spilled" through incompetent superficial veins and re-enters the deep veins at a lower part of the limb.

The high retrograde flow in superficial veins during walking refills the deep veins during muscle diastole, greatly enhancing the venous pump capacity by increasing the expelled volume. The net increase in expelled volume is, however, due to the superficial retrograde circuit and does not represent effectively increased drainage from the extremity. The result of this rapid back-flow is that the systolic pressures in the deep and superficial ankle veins remain high during walking.

Proximal occlusion of the superficial veins normalises ambulatory venous pressure in these veins and the pressure recovery time after standstill. This effect is the dynamic basis for the detection of superficial venous dysfunction by venous pressure measurements. The pressure test does not, however, assess the patency of the perforating veins.

Combined superficial, perforator and deep dysfunction

Whereas the deep, perforating and superficial veins of the leg may all be more or less involved in skin ulcer formation (54-56), deep venous incompetence is involved in most cases (57, 58). Deep venous incompetence is usually secondary to previous deep venous thrombosis (DVT). The venodynamics is characterised by ambulatory venous hypertension in both superficial and deep veins. In this state the capillary pressure at upright position is high, the only relief being elevation of the legs.

During walking, the pressures in superficial and deep veins oscillate around the level during standing passively, i.e. with minimal net reduction in ambulatory venous pressure (Fig. 7). Flow in perforating veins is bi-directional, with an outward net flow (52), as opposed to the situation with superficial and perforator incompetence only (Fig. 6). The flow in superficial veins may be bi-directional, without net flow, or a net flow directed centrally or distally.

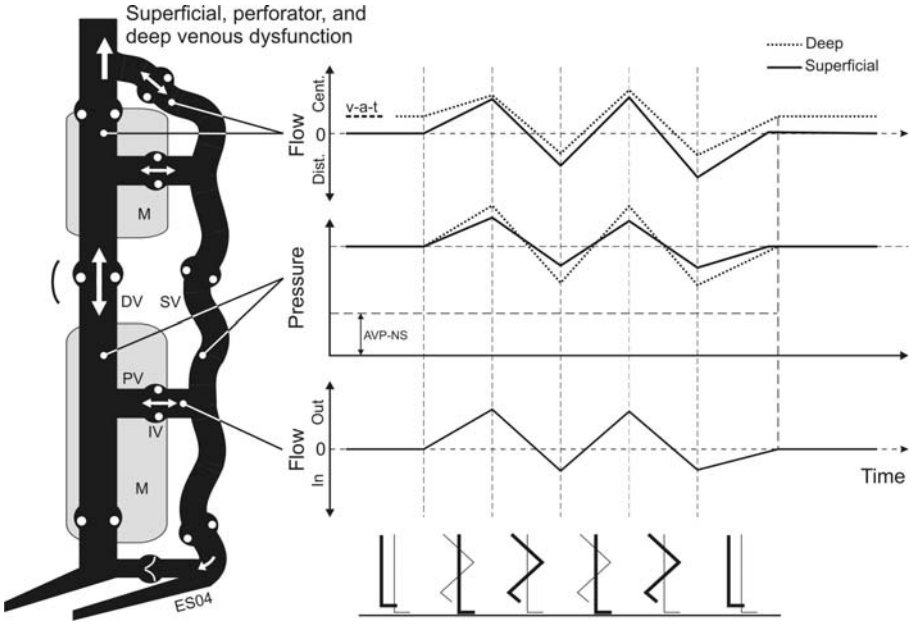

Fig. 7. *Schematic illustration of venodynamics in patients with superficial, perforator and deep venous dysfunction. During walking, the pressures in superficial and deep veins are oscillating around the pressure at passive upright position, i.e. with minimal net reduction in ambulatory venous pressure. Flow in perforating veins is bidirectional, with outward net-flow, the opposite to what is found in patients with superficial and perforator incompetence only (Fig. 6). The flow in superficial veins may be bidirectional, with no net flow, or net flow either centrally or distally. Annotations are as in figure 5.*

Outflow obstruction

Venous outflow obstruction may be the result of occluded or partially recanalized veins subsequent to DVT. In proximal (outflow) venous thrombosis, increased outflow resistance and venous pressure during muscle contraction may lead to venous claudication (Fig. 8).

The ambulatory venous hypertension often leads to distension of the perforators and valve dysfunction (59). The pressure and flow is then directed towards the superficial veins, which may become the principal venous conduits. A resulting overload of the superficial veins may lead to dysfunction, including varicose veins.

Figure 8 schematically demonstrates mean pressure curves during and after ambulation in the four states listed. The ambulatory venous pressure typically increases from healthy subjects - to patients with superficial and perforator dysfunction - to those with additional deep venous dysfunction - and to those with deep venous obstruction. These venous pressure profiles, along

with the recovery times (time from end of walking until the vein pressure reaches the level of passive dependency), without and with superficial venous occlusion (occlusion test), form the diagnostic basis of venous pressure measurements (3).

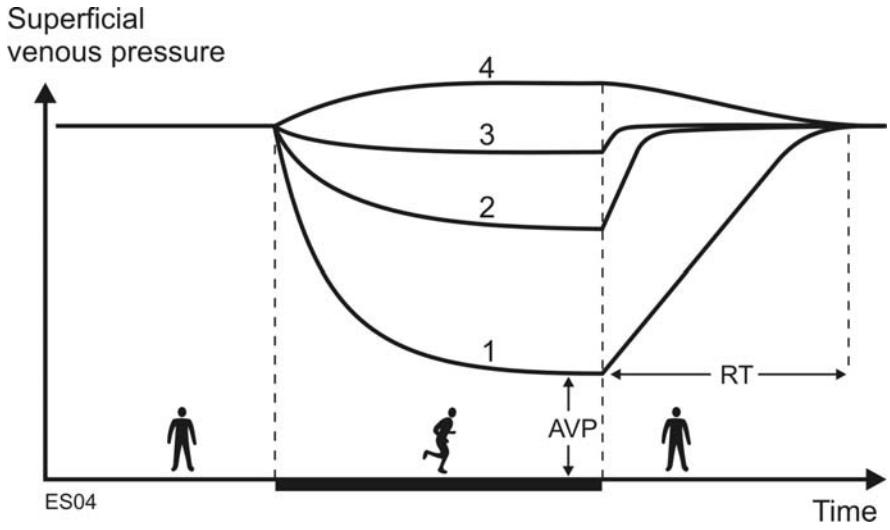

Fig. 8. *Schematic illustration of the superficial venous pressure at rest, and during ambulation (solid horizontal line) in healthy subjects (1), patients with superficial and perforator dysfunction (2), patients with additional deep venous dysfunction (3), and patients with deep venous outflow obstruction (4). The ambulatory venous pressure (AVP) represents the lowest mean pressure during walking at the site of measurement, and the recovery time (RT) is the time interval between the end of walking until the vein pressure reaches the pressure level at passive dependency. In healthy subjects AVP at distal calf is about 30 mmHg and RT is >20s.*

References

1 Burnand KG, O'Donnell TF, Lea Thomas M, Browse NL. The relative importance of incompetent communicating veins in the production of varicose veins and venous ulcers. Surgery 1977; 82: 9-14.

2 Arnoldi CC. Venous pressure in patients with valvular incompetence of the veins of the lower limb. Acta Chir Scand 1966; 132: 628-45.

3 Bjordal RI. Pressure and flow measurements in venous insufficiency of the legs. In: Eklöf B, Gjöres JE, Thulesius O, Bergqvist D, editors. Controversies in the management of venous disorders. London: Butterworths, 1989: 24-35.

4 Gilje O. Ulcus cruris in venous circulatory disturbances. Investigations of the etiology, pathogenesis and therapy of leg ulcers. Acta Derm Venerol (Oslo) 1949; Suppl. 22

5 Coleridge Smith PD, Thomas P, Scurr JH, Dormandy JA. Causes of venous ulceration: a new hypothesis BMJ 1988; 296: 1726-1727.

6 Coleridge-Smith PD. How does a leg ulcerate? In: Ruckley CV, Fowkes FGR, Bradbury AW, editors. Venous Disease: Epidemiology, Management and Delivery of Care. London: Springer Verlag Ltd; 1999. p. 51-70.

7 Coleridge-Smith PD. Update on chronic-venous-insufficiency-induced inflammatory processes. Angiology 2001; 52 (Suppl. 1): S35-s42.

8 Fagrell B. Microcirculatory disturbances - the final cause for venous leg ulcers? VASA 1982; 11: 101-103.

9 Hansson C. Studies on leg and foot ulcers. Acta Derm Venerol (Stockh) 1988; Suppl. 136.

10 Luetolf O, Bull RH, Bates DO, Mortimer PS. Capillary underperfusion in chronic venous insufficiency: a cause for leg ulceration? Br J Dermatol 1993; 128: 249-254.

11 Fagrell B. Microcirculatory disturbances in chronic venous insufficiency (CVI). The Norwegian Medicines Control Authority, Medical Products Agency. Oslo 1995: 87-99.

12 Shepherd JT, Vanhoutte PM. Veins and their control. London: W.B. Saunders Company Ltd., 1975.

13 Thulesius O. Vein Wall characteristics and valvular function in chronic venous insufficiency. Phlebology 1993;

8: 94-98.
14 Attinger EO. Wall properties of veins. IEEE Transact Bio Med Eng 1969; 16: 230-235.
15 Thulesius O. Pathophysiology of venous insufficiency. In: Eklöf B, Gjöres JE, Thulesius O, Bergqvist D, editors. Controversies in the management of venous disorders. London: Butterworths, 1989: 1-5.
16 Griffiths DJ. Principles of flow through collapsible tubes: Venous hydrodynamics. In: Gardner AMD, Fox RH, editors. The return of blood to the heart: venous pumps in health and disease. London: John Libbey & Co. Ltd. 1989: 115-126.
17 Burton AC. Physiology and biophysics of the circulation. Chicago: Year Book Medical Publishers, Inc., 1972.
18 Gardner AMN, Fox RH. The return of blood to the heart: venous pumps in health and disease. London: John Libbey & Co. Ltd. 1989.
19 Arnoldi CC. Physiology and pathophysiology of the venous pump of the calf. In: Eklöf B, Gjöres JE, Thulesius O, Bergqvist D. Controversies in the management of venous disorders. London: Butterworths, 1989: 6-23.
20 Allwood MJ. The effect of an increased local pressure gradient on blood flow in the foot. Clin Sci 1947, 16: 231-239.
21 Ashton H. Critical closing pressure in human peripheral vascular beds . Clin Sci 1962; 22: 79-87.
22 Ashton H. Reopening of blood vessels after critical closure. Clin Sci 1962; 22: 95-100.
23 Ashton H. The effect of increased tissue pressure on blood flow. Clin Orthop 1975; 113: 15-26.
24 Baumann JU, Sutherland DH, Hanggi, A. Intramuscular pressure during walking. Clin Orthop 1979; 145: 292-299.
25 Hach W. Der Phlebographie der Bein und Beckenvenen. Constanz: Schnetzor-verlag GMBH, 1976.
26 Gershuni DH, Yaru NC, Hargens AR et al. Ankle and knee position as a factor modifying intracompartmental pressure in the human leg. J Bone Joint Surg 1984; 66A: 1415-1420.
27 Le Dentuy A. Circulation veineuse du pied et de la jambe. Paris: Adrien Delahaye, 1867.
28 Gardner AMN, Fox RH. The venous pump of the human foot. Bristol Med-Chir J 1983; 98: 109-112.
29 Gardner AMN, Fox RH. The return of blood to the heart against the force of gravity. In: Phlebology '85, ed. D. Negus & G. Jantet, pp. 56-67. London: John Libbey, 1986.
30 Basmajian JV, Bentzon JW. An electromyographic study of certain muscles of the leg and foot in the standing position. Surg Gynecol Obstet 1954; 98: 662-666.
31 Basmajian JV, Steko G. The role of muscles in arch support of the foot. J Bone Joint Surg 1963; 45A: 1184-1190.
32 Klenerman L. Functional anatomy of the foot and ankle. 2. The foot and its disorders. Oxford: Blackwell, 1976.
33 Stranden E, A Aarås, DM Anderson, HO Myhre and K Martinsen. The effect of working posture on musculoskeletal load and circulatory condition. In: Coombs K ed. Proceedings of the Ergonomics Society's Conference 1983. Taylor & Francis Ltd., London. 163-167, 1983.
34 Arnoldi CC. The venous return from the lower leg. A synthesis. Acta Orthop Scand 1964; Suppl. 64: 1-75.
35 Arnoldi CC. Venous pressure in the leg of healthy human subjects at rest and during muscular exercise in the nearly erect position. Acta Chir Scand 1965; 130: 570-583.
36 Arnoldi, CC. The influence of posture upon the pressure in the veins of the normal human leg at rest and during rhythmic muscular exercise. Acta Chir Scand 1966; 131: 423-431.
37 Arnoldi CC, Greitz T, Linderholm H. Variations in cross-sectional area and pressure in the veins of the normal human leg during rhythmic muscular exercise. Acta Chir Scand 1966; 132: 507.
38 Arnoldi CC, Linderholm H. Venous blood pressures in the lower leg at rest and during exercise in patients with idiopathic dysfunction of the venous pump of the calf. Acta Chir Scand 1969; 135: 601-609.
39 Arnoldi CC, Linderholm H. Intracalcanean pressure in various forms of dysfunction of the venous pump of the calf. Acta Chir Scand 1971; 137: 21-27.
40 Bjordal RI. Simultaneous pressure and flow recordings in varicose veins of the lower extremity. Acta Chir Scand 1970; 136: 309-317.
41 Bjordal RI. Pressure patterns in the saphenous system in patients with venous leg ulcers. Acta Chir Scand 1971; 137: 495-501.
42 Bjordal RI. Circulation patterns in incompetent perforating veins on the calf and in the saphenous system in primary varicose veins. Acta Chir Scand 1972; 138, 251-261.
43 Bjordal RI. Blood circulation in varicose veins of the lower extremities. *Thesis*, Universitetsforlaget, Oslo 1973.
44 Bjordal RI. Haemodynamic studies of varicose veins and the postthrombotic syndrome. In: JT Hobbs. The Treatment of Venous Disorders. Lancaster: MTB Press Ltd, 1977: 37-55.
45 Bjordal RI. Die Zirkulation in insufficienten V.V. perforantes der Wade bei venösen Störungen. Klinische und Therapeutische Konsequenzen der beobachten hæmodynamischen Strømungsmuster. In: R May, H Partsch, J Staubesand. Venae Perforantes. München: Urban and Schwarzenberg, 1981: 71-93.
46 Christopoulos D, Nicolaides AN, Cook A, et al. Pathogenesis of venous ulcerations in relation to the calf muscle pump function. Surgery 1989; 106:829-835.
47 Rosfors S, Bygdeman S, Nordström E. Assessment of deep venous incompetence: A prospective study

comparing duplex scanning with descending phlebography. Angiology 1990; 41: 463-468.
48 Gaskell MD, Burton PD. Local postural vasomotor reflexes arising from the limb veins. Circ Res 1953; 1: 27-39.
49 Henriksen O, Paaske WP, Sejrsen P. Autoregulation of blood in human subcutaneous tissue. Acta Physiol Scand 1973; 89: 531-537.
50 Stranden E. Dynamic recording of vasoconstrictor response to increased vascular transmural pressure. Acta Chir Scand 1984; 150: 25-30.
51 Bassi G. L'ulcère et les dermatoses pre-ulcéreuses dans l'insuffisance primitive de la saphène externe. Phlebologie 1974; 27: 119-22.
52 Bjordal R. Flow and pressure studies in venous insufficiency. Acta Chir Scand 1988; Suppl 544: 30-3.
53 Trendelenburg F. Über die Unterbindung der Vena saphena magna bei Unterschenkelvaricen. Beitr Klin Chir 1891; 17: 165.
54 Raju S. Venous insufficiency of the lower limb and stasis ulceration. Ann Surg 1983; 197: 688-897.
55 Darke SG. Reconstructive surgery for chronic venous insufficiency of the lower limb. In: Greenhalgh RM, Jamieson CW, Nicolaides AN. Vascular surgery: issues in current practice. Orlando: Grune & Stratton, 1986: 417-434.
56 McEnroe CS, O'Donnell TF, Mackey WC. Correlation of clinical findings with venous hemodynamics in 386 patients with chronic venous insufficiency. Am J Surg 1988; 156: 148-152.
57 Raju S, Fredericks R. Valve reconstruction procedures for nonobstructive venous insufficiency: rationale, techniques and results in 107 procedures with 2-to 8-year follow up. J Vasc Surg 1988; 7: 301-310.
58 Feuerstein W. Die Etagenlokalisation postthrombotischer Venenveranderungen. Wien klin Wschr 1979; 129: 293-296.
59 Burnand KG, Clemenson G, Whimster I, et al: The effect of sustained venous hypertension on the skin capillaries of the canine hind limb. Br J Sug 1982; 69:41-44