The "After-Drop" in Venous Occlusion Plethysmograms

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Venous occlusion plethysmograms from the dependent foot showed an "after-drop" in volume not seen with the foot at heart level. Factors affecting the development of this after-drop were studied. Blood flow was measured during the after-drop and corresponding changes in venous pressure recorded. The evidence obtained does not support the existing explanation that the after-drop is due to a reflex vasoconstriction. It is suggested that this phenomenon is due to a shifting of blood in the underlying vessels by the venous occlusion cuff.

In 1953 Gaskell and Burton postulated the existence of a reflex vasoconstriction elicited by distension of local veins. They observed that under certain conditions the volume of the digit within a plethysmograph diminished below the resting level on release of the collecting cuff. This decrease in volume they termed the "after-drop." The existence of such a reflex raised serious doubts about the classic plethysmograph method for measuring blood flow. Burton (1954) has drawn attention to the after-drop as a "reactive-error" in plethysmography.

The experiments described here started as a study of blood flow in the dependent foot. An after-drop in volume was observed along with an apparently diminished inflow. Uncertainty as to the correct interpretation of the inflow records, in the light of the work of Gaskell and Burton, led to further experiments on the nature of the after-drop. As a result of these experiments it is believed that the after-drop in volume is not indicative of a reflex vasoconstriction. A simple mechanical explanation of shifting of blood within the extremity by the collecting cuff is in better agreement with observed data. A similar conclusion has been arrived at after further experiments by one of the original authors.

METHOD

Foot blood flow was measured using a water filled plethysmograph of conventional design, except that the funnel was set at an angle between two adjacent faces. This enabled air transmission from the plethysmograph to recorder to continue while the limb was altered from a horizontal to a dependent position. The position of the foot within the plethysmograph was kept constant by a heel support. Water temperature was between 32 and 34°C.

Venous pressure was continuously recorded using an indwelling needle connected to a Hansen capacitance gauge, or from a fine catheter connected to a Southern Instruments blood pressure recorder. In a small number of experiments the venous pressure was measured within a vein of the foot enclosed within the plethysmograph. In the remainder the pressure and volume records were obtained separately.

Subjects were healthy males aged 19 to 36 years. Ambient temperature during the blood flow experiments was 23 ± 1°C.

RESULTS

Development of the after-drop in the dependent limb. The initial experiments were intended to measure foot blood flow when the foot was dependent. With the subject supine the blood flow records were of the usual form, that is, release of the collecting cuff was followed by a fall in volume as the foot emptied, with a decrease in the rate of emptying until the resting volume was regained. On assuming the erect posture the form of the blood flow record altered. Release of the collecting cuff was now followed by a sudden fall in volume below the initial level. The rate of emptying tailed off, an increase in volume followed, and the resting volume was again reached. This decrease below the initial level is the after-drop. The volume of the after-drop was found to increase with the height of the hydrostatic column up to the heart. When a standing subject sat down in a...
Fig. 1. The effect of increasing the local venous pressure on the volume of the after-drop in the foot. Subject supine; local venous pressure elevated by a congestion cuff around the thigh inflated to the pressure shown along the abscissal scale. Collecting pressure 110 mm. Hg throughout.

The volume of the after-drop fell. It diminished further if the feet were raised so that the legs were horizontal. It was not normally seen in the supine posture, but appeared when the shoulders were raised about a foot as an increased acuteness of angle between reverse-artefact and base line. On raising the shoulders further, a definite fall in volume below the resting level occurred.

Development of the after-drop with venous congestion. The increased volume of after-drop with increasing hydrostatic pressure suggested a relationship between the after-drop and local venous pressure. This was confirmed by experiments with the subject supine, but with venous pressure in the limb elevated by a congestion cuff around the thigh. Before the thigh cuff was inflated the blood flow record was normal. On inflating the cuff and causing venous congestion the after-drop appeared. The relationship between after-drop volume and venous pressure was studied for a range of pressures in the thigh cuff. Congestion pressures of 20 mm. Hg and below produced no measurable after-drop. Above this there was a linear relationship between congestion pressure and after-drop volume up to 80 mm. Hg. Between 80 and 100 mm. Hg the gradient diminished, but the congestion cuff now interfered with arterial inflow. Figure 1 shows the effect on the after-drop of increasing local venous congestion using a constant pressure throughout at the collecting cuff.

Width of collecting cuff and after-drop volume.

In the previous experiments in which the local venous pressure was altered either by postural change or use of a congestion cuff, the collecting cuff was unchanged. Experiments were carried out in which the local venous pressure remained constant, but the width of the collecting cuff was altered. Care was taken to adjust the collecting cuff's position so that the distal border was a constant distance from the plethysmograph. The volume of the ankle segment enclosed therefore varied with the cuff width, but the venous bed distally in which collection took place was unchanged. Local venous pressure was elevated by dependancy, or by a congestion cuff around the thigh in the supine subject. With the collecting pressure and local venous pressure constant it was found that the size of the after-drop depended upon the collecting cuff width. The after-drop volume increased with increasing width of cuff (fig. 2a).

A similar result was found when two collecting cuffs were placed side by side round the limb,
and inflated singly or together. Inflation of both was followed by a larger after-drop than inflation of either alone, although the venous bed for collection was identical for the distal and for the double cuff (fig. 2b).

Collecting cuff position and volume of the after-drop. Although the collecting cuff at the ankle was normally placed close to the plethysmograph, as is customary in measuring blood flow, it was possible to obtain after-drops with the cuff elsewhere. The after-drop volume varied with the site of the cuff. It increased initially on moving the cuff higher up the limb, and then diminished. The largest after-drop with a collecting cuff 8 cm. in diameter was obtained with the distal border 20 cm. from the plethysmograph. Here the cuff encircled the widest part of the calf. From the previous observations on cuff width, together with this finding on cuff position, it appeared that the after-drop volume on release of a collecting cuff depended on the volume of the segment enclosed by the cuff.

Duration of collection and after-drop volume. Other things remaining constant, an inverse relationship was found between the duration the collection cuff was inflated and the volume of the succeeding after-drop. This relationship was obtained in the congested limb of a supine subject and when the limb was dependent. "Blipping" the cuff on and straight off was followed by the largest after-drop, while inflation for one minute or longer was generally followed by a very small after-drop or by none at all. Figure 3a shows this relationship graphically. The scatter of points is wide and the relationship well defined only for collections up to 20 sec. duration. This suggested that the essential variable was the volume of blood collected by the cuff and not the duration of collection. Blood flow is constantly changing within limits so that equal collecting times would not result in identical volumes being collected. In addition, collection continues only so long as the collecting pressure is greater than the pressure in the veins distally, the volume record then reaching a plateau. In figure 3b the same observations have been used as in figure 3a, but the volume of blood collected is the abscissa instead of duration of collection. The inverse relationship is now clearer, showing that the more blood collected within the plethysmograph the smaller is the volume of the succeeding after-drop.

After-drop in a limb with arterial occlusion. When the arterial inflow to a limb was occluded by a pressure of 250 mm. Hg in a thigh cuff, a further difference was noted between the volume record from a congested and an uncongested limb. In the uncongested limb with the blood supply cut off inflation and deflation of the collecting cuff at the ankle gave a "square wave" record. This consisted of a cuff artefact followed by a plateau since there was no inflow with a reverse artefact back to the initial volume. In the limb with veins initially distended the reverse artefact was followed by a decrease in volume below the resting level. This after-drop was not followed by a return to the initial volume, for there was no inflow. Successive collections resulted in further after-drops, each without a return in volume, but the size of the after-drops became progressively smaller until a basal volume within the plethysmograph was reached. Further collections now gave the square-wave record as in the uncongested limb.

Successive collecting cuff inflations and after-drops. The phenomenon of repeated collecting cuff inflations causing successive diminutions in volume was also observed in the limb with venous congestion but without arterial occlusion. As in the previous experiments it made
no difference to the results if venous congestion was caused by an inflated cuff proximally or by dependency. Provided the collecting cuff inflation and deflation took place before the volume had recovered from the previous after-drop, the next after-drop caused the volume to fall below that of its predecessor. Therefore it was best seen with very brief cuff inflations in rapid succession, for in this case there was very little recovery in volume from one after-drop before the advent of the next. Successive falls in volume became progressively smaller until a basal volume was reached within the plethysmograph. Figure 4 shows collections in rapid succession with a basal volume reached after the fourth inflation.

**Rate of blood flow during the after-drop.** Inflation of the collecting cuff during an after-drop enabled blood flow at that time to be measured in the normal manner. The usual procedure was to "blip" the collecting cuff on and off, which resulted in the largest after-drop as shown above. The cuff was then rapidly reinflated and left on while a suitable collection occurred (usually between 5 and 10 secs). The rate of inflow was then compared with collections made in the customary manner, and not following after-drops. The blood flow to the foot during the after-drop was greater than the resting inflow. This result, which is considered to be most important confirmatory evidence for the mechanical as opposed to the existing explanation, is also seen in figure 4. Here the inflow during the after-drop was twice as great as the resting blood flow to the foot.

**Foot venous pressure during the after-drop in volume.** Venous pressure was measured in a superficial vein of the foot in eleven experiments while on three further occasions venous pressure was recorded from a vein enclosed within the plethysmograph. Most of the characteristics of the after-drop which have so far been described were investigated. Because of the number of points investigated and the relatively few experiments the venous pressure results have little quantitative significance. They should be regarded qualitatively and they show that pressure changes parallel volume changes in the venous bed of the foot. An after-drop in pressure was obtained in all cases where an after-drop in volume would be expected, and the factors influencing its development were the same. In a limb without congested veins, such as a supine subject with the foot at heart level, the venous pressure rose when the collecting cuff was inflated, and returned to normal on deflation. If the limb was now lowered, or a venous congestion cuff inflated around the thigh, release of the collecting cuff at the ankle was followed by an after-drop in venous pressure with recovery to the resting level. The magnitude of the after-drop in pressure depended on the initial local venous pressure. The greater this initial pressure the greater was the after-drop in pressure. It depended also on the width of the collecting cuff, being greater with a wider cuff. Similarly, the pressure record paralleled the volume record with alteration in duration of collection. The largest fall in pressure followed the briefest inflation; collections lasting forty seconds or more were usually not followed by a fall in pressure. Successive inflations of brief duration and at short intervals resulted in further falls in pressure but these after-drops progressively diminished until a basal pressure was reached (fig. 5). Only in the record during arterial occlusion was a difference seen between venous pressure and volume. The volume diminished and remained at that level because there was no inflow. The pressure also fell with an after-drop, but there was then a slow recovery to midway between the resting and the after-drop pressures. This may have been due to incomplete arterial occlusion with a leak past the cuff, or to a collateral inflow through bone, but
Fig. 5. Venous pressure (above) and foot volume (below) showing simultaneous fall in pressure and in volume caused by frequent cuff inflations in rapid succession. Collecting pressure 90 mm Hg. Subject tilted 45° to horizontal. Time signal 1 sec.; venous pressure in mm Hg; volume change in ml.

This was unlikely for the pressure would not remain at the intermediate level but would continue rising as more blood entered. It was thought that the rise in venous pressure following the after-drop was due to the establishment of a static equilibrium in a limb with arterial occlusion.

Discussion and Interpretation

The initial experiments in this study had been carried out before the author became aware of the paper by Gaskell and Burton. These early experiments were concerned with measurement of blood flow by venous occlusion plethysmography in a dependent limb. The occurrence of the temporary fall in volume following release of the collecting cuff was noted. This volume decrease was first described by Abramson, Zazeela and Marrus in 1939. They believed it indicated a local reflex vasoconstriction and observed that the response was only seen on removal of the stimulus. The importance of the rediscovery of this phenomenon by Gaskell and Burton during digital plethysmography lay in the conclusions drawn from their interpretation of it. Abramson and associates noted that the response was only observed on release of the collecting cuff. Gaskell and Burton believed it occurred as soon as the cuff was inflated if the veins were already full. This raised doubts about the classic venous occlusion plethysmography method under these conditions, for the reflex would occur during measurement. The normal inflow curve therefore gave an apparent rate of inflow only; to allow for the reflex the values should be corrected. The method of correction was to use, as a baseline for measuring the slope of the inflow, a line joining the volume record at the start of occlusion to the lowest point of the after-drop. It was this concept of apparent and corrected flows that led to these further experiments, for it was believed that the basis of the corrected flows was unsound. By leaving a collecting cuff inflated longer than was intended, a different after-drop and therefore a different baseline for inflow measurement would result. One inflow curve could give a variety of flow values depending on how long the investigator allowed the cuff to remain inflated.

It is thought that this temporary fall in volume, and in pressure, is due to a shifting of blood in the veins by the cuff. In a limb with distended veins inflation of a collecting cuff squeezes blood out of the veins beneath. If the valves are competent, most of this blood is propelled proximally. Release of the cuff is followed by a refilling of the previously emptied vessels. Because of the venous valves this refilling takes place with blood from the segment distal to the cuff. If the volume of the blood squeezed out is large in comparison to the volume collected by the cuff, then more blood may leave the distal veins to refill the emptied segment than has been collected. The net result is a temporary fall in volume of the part distal to the cuff. If this is enclosed within a plethysmograph the volume record will show an after-drop. The same explanation of blood leaving one part of a limb to refill a segment previously emptied will account for the after-drop in venous pressure.

The finding that the after-drop in pressure and in volume is larger on standing than on sitting and, similarly, is larger with increasing venous congestion initially, is due to more blood being emptied out of distended veins by the cuff, with a larger deficit to be refilled. These findings also fit in with the reflex vaso-
constriction theory of Gaskell and Burton, for the greater the distension the larger would be the reflex. The remainder of the findings are difficult to explain on their theory.

It is difficult to see why increasing the width of cuff should increase the size of the reflex if the vascular bed beyond the cuff is unchanged, for the stimulus to the reflex, viz., venous distension, is unaltered. But the mechanical theory explains this and also why the largest after-drop occurred with the cuff 20 cm. above the plethysmograph. In the first instance the wider cuff empties out more blood, resulting in a greater volume of blood to refill; in the second the increased girth of calf and greater proportion of muscle also results in more blood being expelled, with a larger subsequent after-drop. A possible explanation for the relationship between cuff width and after-drop volume would be that the phenomenon was a reflex vasoconstriction elicited by pressure on receptors somewhere beneath the cuff. Abramson and associates may have had this possibility in mind.

That the after-drop is unlikely to be due to a vasoconstriction will be explained later. The finding that the after-drop was larger with a cuff midway up the calf was at first unexpected. It was thought that as the cuff was moved away from the plethysmograph the after-drop would diminish, for an increasing proportion of tissue distal to the cuff would be outside the plethysmograph. It is conceivable that if the lower leg were a uniform cylinder this would be the case. As the calf widens above the ankle the magnitude of the after-drop is a compromise between an increase due to increasing volume of tissue beneath and a decrease due to a larger fraction of the venous bed interposed between cuff and plethysmograph.

The results of altering the collecting time form important evidence in favour of the mechanical theory. The longer the collecting cuff is inflated the greater will be the volume of blood collected distally. Conversely "blipping" the cuff straight on and off will empty the segment below without allowing time for much blood to collect. Hence the largest after-drops follow the briefest inflations. In addition, if the cuff is left inflated until the volume record starts to tail off, blood will have started to refill the emptied veins beneath the cuff. The longer the cuff is inflated therefore not only is the volume collected greater, but the volume to be refilled is diminished. The vasoconstriction theory cannot explain these findings, for the longer the cuff is on, and the higher the venous pressure distally, the greater would be the stimulus for the reflex. In this case, the after-drop should increase with increasing duration of collection and with increasing distension.

The occurrence of an after-drop in volume following cuff deflation in a limb with the blood supply occluded is not necessarily at variance with the reflex theory. There seems no reason why a reflex constrictor response should not be elicited by a stimulus although there is no inflow. The continuation of the vasoconstriction for the duration of the arterial occlusion is, however, difficult to explain on these grounds, for the stimulus for the reflex was considered to be local venous distension and this stimulus ceased when the collecting cuff was deflated. On the mechanical basis, release of the collecting cuff is followed by a partial emptying of the veins distally to refill the emptied segment. The after-drop persists because there is no arterial inflow into the foot to refill these partially emptied veins.

Brief cuff inflations in rapid succession cause more blood to be propelled forwards than has collected in the short periods of inflation. Therefore the volume distally falls. This fall in volume does not go on indefinitely for most of the refilling of the venous bed beneath the cuff takes place from these distal veins and, if they are being emptied, successive cuff inflations result in smaller and smaller after-drops. Eventually an equilibrium is reached with the inflow into the distal bed equaling the volume going to refill the veins beneath the cuff. The rapidly inflating and deflating cuff acts as a pump emptying the distal reservoir. This process has been termed "milking." The venous pressure record here is of particular importance. "Milking" causes the venous pressure, as well as the volume, to fall (fig. 5). If distension of local veins were the stimulus for a vasoconstriction, the reflex should be in abeyance for
the pressure is lowered during these rapid inflations.

The venous pressure records, as previously stated, should be regarded qualitatively, for in general they are too few for quantitative assessment. They confirm the volume experiments; in particular they show that rise of pressure locally is unlikely to be the stimulus, if the after-drop is a reflex, for the after-drop may follow the briefest of inflations during which time the venous pressure distally has not started to rise.

However, the experiments which are considered to provide the strongest evidence against the reflex vasoconstriction theory are those in which blood flow has been measured during the after-drop. If this volume decrease was due to a vasoconstriction, the resistance to flow would increase and the blood flow during vasoconstriction should diminish. These experiments showed, quite definitely, that the inflow was increased during this time. The explanation is that, in a limb with venous distension, either from a congestion cuff or from body posture, the after-drop increases the local arteriovenous pressure gradient, for the arterial pressure is unchanged but the local venous pressure falls. This fall in venous pressure has been seen on almost every occasion when the duration of collection was half a minute or less. The increased arteriovenous pressure gradient causes the increase in blood flow locally.

Finally, the after-drop in pressure is a well recognised physiologic phenomenon in the lower extremity. Pollack and Wood,7 and Walker and Longland8 have studied the fall in venous pressure in a superficial vein of the foot on standing and on exercise. They have shown that contraction of the calf muscles is followed by a fall in venous pressure distally. This fall in local pressure on exercise has also been used as a test of competence of venous valves.5, 10 The after-drop seen during venous occlusion plethysmography is therefore a variation of this normal phenomenon, the underlying veins being emptied by the collecting cuff instead of by the tension of the contracting muscles.

Summary

Blood flow has been measured in the human foot by venous occlusion plethysmography. With the foot dependent the resultant plethysmography trace differed in form from that obtained with the foot at heart level. In the dependent foot the release of the collecting cuff was followed by an "after-drop" in volume.

The after-drop was obtained in the supine subject if the local venous pressure was elevated by a congestion cuff. Factors affecting the after drop have been examined. In addition to the local venous pressure, the volume of the after-drop depended upon the width of the collecting cuff, the position of the collecting cuff and the duration of collection.

Venous pressure in a superficial vein of the foot showed a similar after-drop on cuff deflation and was influenced by similar factors to the volume record.

Consideration of the factors affecting the after-drop in pressure and in volume, and measurement of blood flow during the after-drop, throws doubt on the validity of the existing explanation of this phenomenon.

It is suggested that the after-drop is mechanical in origin, the collecting cuff acting on the underlying veins in a similar manner to contracting muscle, and forming a mechanical "muscle-pump."

Summario in Interlingua

Esseva mesurate le fluxo de sanguine in le pede human per medio de plethysmographia a occlusion venose. Con le pede in position pendente le resultante plethysmography differeva ab illo obtenite con le pede al nivello del corde. In le pede pendente le relaxation del bracial collectori esseva sequite per un "post-cadita" del volumine.

In le caso de subjectos jacente, le "post-cadita" esseva obtenite si le pression venose local esseva elevate per un bracial de congestion. Factores que affiche le post-cadita ha essite examine. Le volumine del post-cadita dependeva non solmente del pression venose local sed etiam del largor del bracial collectori, del
position del bracial collectori, e del duration
del collection.

Le pression in un vena superficial del pede
monstrava un simile cadita post deflation e
esseva influentiate per simile factores.

Le consideration del factores que affice le
post-cadita in pression e in volume e le
mesuration del fluxo sanguineo durante le
post-cadita forna a dubitar del validitate
del currente explication de iste phenomeno.

Nos presenta le theoria que le post-cadita es
de origine mechanic; le bracial collectori age
super le vena subjecente plus o minus como un
musculo que es contrahite e assi forma un
mechanic "pumpa muscular."

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