THE ORIGIN OF INVERTED WAVEFORMS IN THE REFLECTION PLETHYSMOGRAM

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SUMMARY

In reflection plethysmography at the finger inverted pulsewaves are sometimes observed, especially when, during anaesthesia, arterial pressure is measured in the same arm with an inflatable cuff. The origin of this inversion is investigated in two series of experiments with volunteers. In the first series of experiments the influence of the pressure in the upper arm cuff was investigated and in the second series the influence of the application pressure of the transducer on the finger. It is concluded that inversion of the pulse waves of the plethysmogram is a local phenomenon restricted to the reflection method. It is caused by a relative increase in the optical density of the surrounding tissue in relation to the arterial vessels. In the finger it is brought about by venous engorgement and it is dependent on the applied pressure.

Photoelectric plethysmography is often used during anaesthesia to monitor the peripheral circulation (Otteni, Sauvage and Gauthier-Lafaye, 1969, 1970, 1971; Dorlas, 1974; Johnstone, 1974a, b; Körner, 1974; Sara and Shanks, 1978).

The plethysmogram is most often detected by the reflection method from the distal phalanx of a finger and it is sometimes observed that inverted pulse waves occur. This is a temporary phenomenon which may be seen during anaesthesia when arterial pressure is measured in the same arm with an inflatable cuff (fig. 1). Before and after the pressure measurement the plethysmogram shows the normal waveform. We observed inversions when the reflection plethysmogram was taken from the radial artery and Weinman, Hayat and Raviv (1977) found these inversions at the carotid artery by changing the position of the transducer in relation to the artery.

It is notable that inversions are never seen in the transmission plethysmogram.

The inversions in the reflection plethysmogram during anaesthesia could be reproduced easily after we realized that, besides venous engorgement, the application pressure of the transducer also plays a part. Therefore the importance of these factors for the origin of the inversion phenomenon was investigated in two series of experiments with volunteers.

METHODS

The experiments were performed on 10 healthy volunteers, eight men and two women, varying in age from 22 to 55 yr. After some preliminary trials the following experimental arrangement proved to be appropriate. The volunteers sat with the measuring arm resting on a soft support with the elbow slightly flexed. The fingers were dependent, about 30 cm below heart level. At the distal phalanx of the index finger, a reflection transducer was fixed with the aid of a small inflatable cuff. At the little finger of the same hand a transmission transducer was fixed. Both transducers (Philips monitoring system type XV 1504/10) function within the infra-red spectrum. A normal inflatable arterial pressure cuff was attached around the upper arm.

In the first series of experiments the influence of the pressure in the upper arm cuff was investigated, while the pressure in the finger cuff was maintained constant at 20 mm Hg to obtain a good attachment of the transducer at the finger.

The upper arm cuff was first inflated, within 5–10 s, until the pulse waves of the plethysmogram had disappeared and then slowly deflated over about 1 min. After the inversion phenomenon was obtained the experiment was repeated twice with an interval of 10–15 min.

In the second series of experiments the influence of the application pressure of the transducer was investigated. The upper arm cuff was first inflated to greater than the systolic arterial pressure and then slowly deflated until the reflection plethysmogram showed clearly recognizable inversions. With the pressure in the upper arm cuff kept constant at this pressure, the pressure in the finger cuff was first increased in 10-mm Hg steps until the pulse waves...
in the plethysmogram had disappeared and subsequently reduced stepwise until the original pressure was reached.

The application pressure of the transmission transducer on the other finger was not changed during these experiments.

The reflection and transmission plethysmograms were simultaneously recorded on a two-channel recorder (Philips AR 200). The pressure in the upperarm and finger cuff were read and noted at each alteration.

RESULTS
In all volunteers, independent of age or sex, the same pattern of results was obtained.

Figure 2 shows a typical example of the results in the first series of experiments. When the pressure in the upper arm cuff decreased to less than the systolic pressure (120 mm Hg) the pulse waves in both plethysmograms returned, but those of the transmission plethysmogram had normal waveforms whereas those of the reflection plethysmogram were inverted. At progressive slow deflation of the upper arm cuff the amplitude of the transmission plethysmogram increased gradually to the original value. The amplitude of the inverted reflection plethysmogram initially increased, but after a stable period it suddenly decreased (at about 45 mm Hg) and became minimal at about 35 mm Hg. Still further reduction of the arm cuff pressure resulted in the return of the normal waveform of the reflection plethysmogram with an increase in amplitude up to the original value.

Figure 3 shows a typical example of the second series of experiments. These started with an inverted reflection plethysmogram brought about by the deflation of the upper arm cuff to about 60 mm Hg. Increasing the pressure in the finger cuff, in steps of 10 mm Hg, caused small increases in amplitude of the inverted reflection plethysmogram, until at about 70 mm Hg the amplitude and the waveform became hardly recognizable. Increasing the pressure in the finger cuff stepwise again produced a return of the normal waveforms. The amplitude first increased, but disappeared when the systolic pressure was reached.

On subsequent stepwise deflation of the finger cuff, the reverse sequence of events occurred, so that at pressure less than about 70 mm Hg the reflection plethysmogram became inverted again and its amplitude declined to its starting value. During these experiments the transmission plethysmogram, taken from the little finger of the same hand, did not change.

DISCUSSION
In photoelectric plethysmography tissue is illuminated by a small light source. In the tissue the emitted light is partly absorbed and scattered. The remaining part emerges from the tissue and can be detected by a photoelectric cell. The intensity of the detected light shows small changes synchronous with the arterial blood pulsations, giving rise to the plethysmogram. Whether such a small change in detected light, caused by an arterial pulsation, means an increase or decrease in light emerging from the tissue, depends on several optical factors. The absorption coefficient of blood is very high, so...
Fig. 2 Difference in waveform between the reflection and the transmission plethysmogram on deflation of the upper arm cuff. Abbreviations as figure 1; transm. pleth. = transmission plethysmogram.

Fig. 3. Reflection plethysmogram from the finger during venous engorgement and stepwise changes in application pressure in the finger cuff. Abbreviations as figure 1; FCP = finger cuff pressure.
that during an arterial pulsation slightly more of the emitted light is absorbed. However, both the erythrocytes present in the blood and the moving vascular walls have reflecting properties also. During an arterial pulsation the erythrocytes orientate in the direction of the flow (Visser et al., 1976) and the vascular walls expand. This results in slightly more reflection of the emitted light. Arterial pulsations therefore have, besides the effect of an increase in absorption, the effect of an increase in reflection of the emitted light. The influence of this dual effect is different for transmission and reflection plethysmography.

In transmission plethysmography reflected light is not detected. The plethysmogram is therefore only determined by changes in transmitted light and during arterial pulsations the increase in absorption and in reflection of the emitted light have the same effect of a decrease in transmitted light. In reflection plethysmography, however, the increase in absorption and the increase in reflection of the emitted light during arterial pulsations have a contrary effect upon the resulting change in emerging light detected. Which of these two contrary effects will predominate depends upon the reflecting properties of the embedding tissue, as we have shown in a previous paper (Nijboer, Dorlas and Mahieu, 1981). This was also demonstrated by Weinman, Hayat and Raviv (1977) in their in vitro experiments with isolated blood vessels embedded in agar. The reflection of blood volume pulsations in these vessels was measured against a background which was changed from bright to dark. Two clearly different situations could be distinguished:

(1) against a bright, strongly reflecting background the blood pulsations produced a decrease in the intensity of reflected light, which caused normal wave forms in the plethysmogram.
(2) against a dark, strongly absorbing background the blood pulsations produced an increase in the intensity of reflected light and consequently an inverted plethysmogram.

Against a background of brightness between these two extremes, normal or inverted and sometimes no pulse waves were found.

In our previous paper (Nijboer, Dorlas and Mahieu, 1981) it was demonstrated that the normally perfused finger reflects a considerable amount of light. This must be reflection from the skin and other tissues, because a bloodless finger reflects even more light than a perfused finger. The first series of the present experiments started with a normally perfused finger and against this bright embedding tissue the domination of the absorbing effect of the blood pulsation is bound to cause the normal waveform in the reflection plethysmogram (comparable to condition 1 of Weinman, Hayat and Raviv (1977)). However, with inflation and subsequent deflation of the cuff around the dependent arm to less than systolic pressure, venous engorgement occurs, which may indeed change the optical background from bright to relatively dark. Against this dark embedding tissue the reflecting effect of arterial pulsations may dominate over their absorbing effect, giving rise to inversion of the reflection plethysmogram (compare condition 2 of Weinman).

The increase in amplitude of the inverted waves, following progressive deflation of the arm cuff to the diastolic pressure, can be ascribed mainly to a growing pulse pressure. When the arm cuff pressure decreases to less than 45 mmHg, the venous engorgement diminishes so that the embedding tissue regains its normal brightness and the inverted waveforms revert to the normal plethysmogram, with increasing amplitude up to the original value.

The transmission plethysmogram always has the normal waveform because venous engorgement only causes less light to be transmitted. Its gradual increase in amplitude on deflation of the upper arm cuff is mainly caused by the growing pulse pressure. The results of the second series of experiments show that the application pressure of the transducer is important to the inversion phenomenon. De Pater, van den Berg and Bueno (1962) have demonstrated that the amplitude increases when the application pressure is increased to 50–60 mmHg. This was obviously the case with the inverted waveform which was brought about by venous engorgement in the dependent arm at the start of these experiments.

The change from inverted to normal waveforms, when the finger cuff pressure is increased from 70 to 80 mm Hg, must again be a result of change in the optical density of the embedding tissue. The application pressure then passes the local venous engorgement pressure so that part of the venous blood is pushed away. The more venous blood is pushed away the more the amplitude increases, but it decreases again when the application pressure comes near to the systolic pressure. The reverse sequence of events, occurring on subsequent reduction of the finger cuff pressure, is explained in a similar way.

The transmission plethysmogram simultaneously recorded from another finger of the same hand does not show any changes. This only demonstrates that inversion is a local phenomenon restricted to the reflection method.
From these experiments we conclude that inversion is caused by a relative increase in optical density of the surrounding tissue $v.$ the arterial vessels. In the finger it is brought about by an interaction between venous engorgement and application pressure. This explains why, during anaesthesia, it may be more easily reproduced when the arm lies well below heart level and the application pressure does not exceed 50–60 mm Hg. It can always be observed, independent of age, sex and state of health of the patients, when in these circumstances arterial pressure is measured in the same arm with an inflatable cuff.

REFERENCES


