PHOTO-ELECTRIC PLETHYSMOGRAPHY AS A MONITORING DEVICE IN ANAESTHESIA

Application and Interpretation

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Photo-electric plethysmography can be used during anaesthesia to monitor the pulsations associated with changes in blood volume in a peripheral vascular bed, and may be useful as a detector of imminent haemodynamic disturbance (Foster, Neumann and Rovenstein, 1945; Dorlas and Zeelenberg, 1970; Otteni, Sauvage and Gauthier-Lafaye, 1970). When displayed continuously on an oscilloscope, the plethysmograph indicates electro–mechanical dissociation (Kleine, Dorlas and Moesker, 1972) and arrhythmias clearly (Sara and Shanks, 1978). Furthermore, it can detect the responses of the autonomic nervous system to stressful stimuli (Kumazawa, Kobayashi and Takagi, 1964; Johnstone, 1967), and the effects of anaesthetic drugs (Dorlas, Bartstra and Zeelenberg, 1969; Körner, 1974). It may be used as an adjunct in the Allen's test (Allen, 1929; Brodsky, 1975). The device is non-invasive, and can be applied easily and rapidly.

However, despite these advantages, the method is not applied universally. This may be because of unfamiliarity with the method as well as doubts about its validity. Thus, we review some fundamental aspects and our own experience from 500 continuous recordings in this article (in a following paper the differences between finger and ear plethysmography will be discussed).

PHOTO-ELECTRIC PRINCIPLE

The basic principle behind the method, first reported by Hertzman (1938), is relatively simple. A small light source and a photo-sensitive detector (photo-electric cell) are attached to an appropriate part of the skin (fig. 1). The emitted light is scattered and partly absorbed in the tissues. Another part of the

SUMMARY

The optical principle of photo-electric plethysmography is described and the clinical significance of changes in the amplitude of the plethysmogram discussed. Physiologically, changes in blood volume pulsations depend on the distensibility of the vessel wall as well as on the intravascular pulse pressure. The importance of both factors in the interpretation of changes in the arterial pulse amplitude is illustrated by examples from 500 continuous recordings. In addition, it is shown that changes in the height of ventilatory waves may be of diagnostic significance.

light emerges again through the skin and is detected by the photo-electric cell. The latter can be positioned either beside, or opposite, the light source, resulting in the reflection or transmission method, respectively. The intensity of the light detected by the photo-cell is determined by the opti-
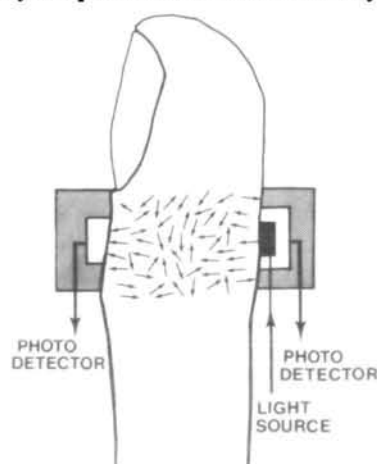

FIG. 1. Application of photo-electric transducer to the finger in the reflection and transmission modes.

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cal density of the solid tissues such as skin, connective tissue and bone, and by that of the varying amount of blood in the vascular bed (Weinman and Manoach, 1962). Blood has a light absorption coefficient which is higher than that of the surrounding tissues (Kramer et al., 1951; Zijlstra and Mook, 1962), so that increases in the amount of blood give rise to a decrease in the total amount of light detected (Challoner and Ramsey, 1974; Challoner, 1979). On the other hand, the erythrocytes (Jansonius, 1959) and the vessel walls (Weinman, Hayat and Raviv, 1977) also reflect some light and, when blood flow is pulsatile, this reflection will increase simultaneously with the pulsations because of the orientation effect of the erythrocytes (Visser et al., 1976), and the movement of the vessel walls. Normally, however, the effect of absorption predominates (Nijboer, Dorlas and Mahieu, 1981), so that arterial pulsations will produce small reductions in the light detected, synchronously with the heart beat. These variations are only small and proportional (1–2%) to the total amount of light detected. Only the variations in detected light are amplified and converted to a voltage signal which can be displayed continously, and recorded as a plethysmogram. In most plethysmographs a decrease in light is recorded as an upward deflection in the plethysmogram. For the recordings reviewed in this article, the Philips peripheral pulse module (type XV 1504/00) (Now: Honeywell Medical Electronics, Best, The Netherlands) was used. Its transducer consists of a diode emitting near infrared light and a matching photo diode for detection.

Since the signal is also electronically chopped, the transducer is relatively insensitive to ambient light and does not produce heat. The transducer is attached to a finger or ear where pulsations in the cutaneous vascular bed are measured almost exclusively (Hertzman, 1938).

ORIGIN AND MEANING OF THE PLETHYSMOGRAPHIC WAVES

Figure 2B shows the photo-electric finger plethysmogram of an anaesthetized patient, recorded at two different paper speeds. Two wave forms can be distinguished. The rapid excursions are synchronous with the heart beat. They arise because volume distensions of the root of the aorta are propagated along the walls of the vascular tree to the terminal arterial bed from which the plethysmogram is recorded. The slower waves are caused by ventilation-dependent changes in intrathoracic pressure, which are transmitted to the periphery (Foster, Neumann and Rovenstein, 1945; Otteni, Sauvage and Gauthier-Lafaye, 1970; Sara and Shanks, 1978). These pressure changes produce variations in blood volume which arise principally in the venous bed, since the venous compliance is 10 times greater than the arterial (Wilkins and Bradley, 1946). These "ventilatory waves" (a more appropriate description than respiratory waves), become especially prominent during artificial ventilation or airway obstruction. The arterial pulse wave is generally used for monitoring purposes (Elings, 1959) because its amplitude indicates the arterial blood pulsations reaching the periphery. However, during anaesthesia, and especially when recorded with a low paper speed, the amplitude of the arterial pulsations is sometimes difficult to distinguish from the ventilatory waves upon which the arterial pulsations are superimposed. This influence of the ventilatory waves may be decreased by the elevation of the measuring site above heart level, so that the venous system will collapse and the changes in intrathoracic pressure are no longer transmitted. However, during anaesthesia this manoeuvre may not suffice. Therefore, a new kind of peak detector has been developed (Sluiter et al., 1981) which calculates the
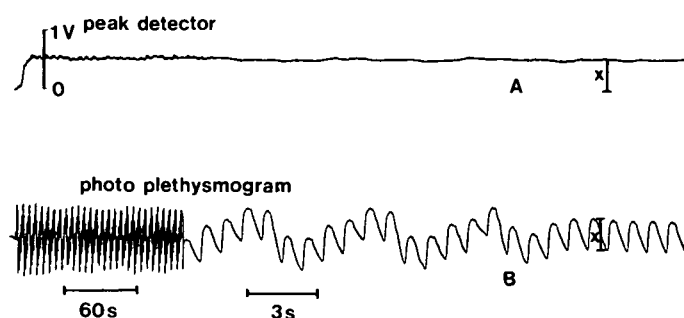
FIG. 2. Photo-electric finger plethysmogram recorded with two paper speeds. A: Arterial pulse amplitude calculated by a peak detector which is not influenced by ventilatory waves. B: Rapid arterial waves and slower ventilatory waves. At the right side the ventilation is stopped temporarily.

peak-to-peak amplitude of each arterial pulse wave and eliminates the slower ventilatory component (fig. 2A). In this paper the peak detector signal is shown only when the exact course of the arterial pulse amplitude is accentuated.

For the interpretation of the photo-electric plethysmogram, it should be realized that changes in light are measured which are proportional to the total amount of light detected and which cannot be calibrated (Nijboer, Dorlas and Mahieu, 1981). Therefore, the amplitude of the photo-electric plethysmogram does not indicate the height of the arterial pulse waves in a quantitative way. All the same, several authors (Elings, 1959; Hertzman, 1959; Zijlstra and Mook, 1962) have reported a good correlation between finger photo-plethysmographic amplitude and the blood flow in the finger.

We have also compared photo-electric plethysmography with mercury-in-rubber strain-gauge plethysmography, the latter being applied in the a.c. mode, without applying venous occlusion, so that only the arterial blood volume pulsations were measured. The plethysmograms were recorded simultaneously from adjacent fingers during anaesthesia (fig. 3). The changes in amplitude of both plethysmograms proved to be identical in 98% of the total number of changes recorded in 104 patients (Nijboer, Dorlas and Prins, 1983). This means that changes in the amplitude of the photo-electric plethysmogram, just like the blood volume pulsations (ΔV), depend on the distensibility of the vascular wall (D) as well as on the intravascular pulse pressure (ΔP). This relationship was given by Burton (1972) as $\Delta V = D.\Delta P$.

In the peripheral arterial bed, the distensibility factor depends mainly upon the tone of vascular smooth muscle, which is controlled by the autonomic nervous system. As a result of the special mechanical arrangement of vascular smooth muscle fibres (Burton, 1954), the effect of autonomic

impulses upon distensibility will be so strong that it completely predominates over the effect of pulse pressure in several regions of the body.

PHYSIOLOGICAL EFFECTS AND INTERPRETATION

Burch, Cohn and Neumann (1942) reported several kinds of autonomic fluctuation arising rhythmically but apparently spontaneously in the plethysmogram of conscious volunteers. Although some investigators considered that there was a connection with central temperature regulating mechanisms (Blair, Glover and Roddie, 1959; Burton and Taylor, 1940), there is still some controversy about their origin. From the autonomic fluctuations and the simultaneously recorded peak detector signal (fig. 4), we conclude that the variations in amplitude in the arterial pulse wave are small. Therefore, the autonomic fluctuations must be the result of changes in the total amount of detected light, which are predominantly determined by volume changes in the venous bed. Since the cutaneous veins are sympathetically innervated (Hertzman, 1959; Shepherd and Vanhoutte, 1975) and play an important part in the regulation of body temperature (Goetz, 1950), an association with this temperature mechanism seems plausible. The autonomic fluctuations always disappear, as Wilson (1936) observed in dogs and rabbits, on the induction of anaesthesia (Burton and Taylor, 1939; Nijboer and Dorlas, 1985). Throughout anaesthesia, on the other hand, shorter or longer-lasting periods of diminished arterial pulse wave amplitude were often noticed in the finger plethysmogram (fig. 5). The decreases in amplitude were connected with pain and stressful stimuli, but
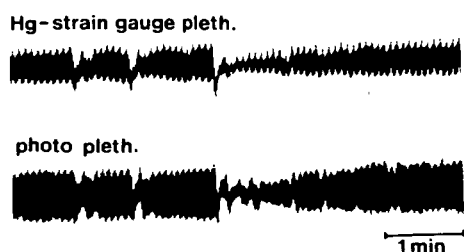

FIG. 3. Vasoconstriction during surgery recorded simultaneously from a finger with photo-electric plethysmography and mercury-in-rubber strain gauge plethysmography.
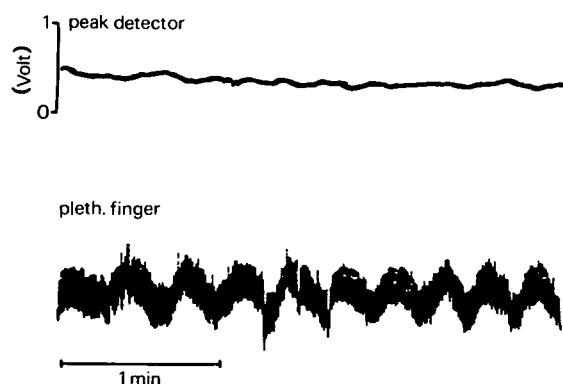

FIG. 4. A: Autonomic fluctuations in the finger plethysmogram of an awake patient. B: Peak detector signal showing that the variations in the amplitude of the arterial pulsations do not reflect the strong fluctuations in the plethysmogram.
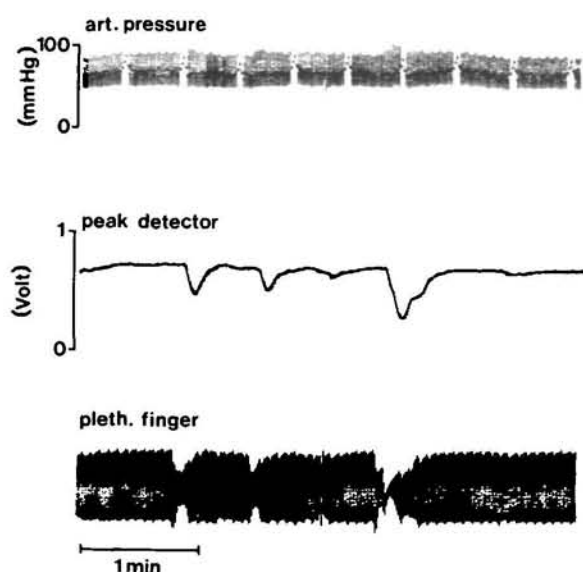
FIG. 5. Vasoconstriction in the finger plethysmogram during surgery which is not accompanied by concomitant decreases in the simultaneously recorded arterial pressure.

were not accompanied by a decrease in pulse pressure (ΔP). Therefore they have to be attributed to a decrease in distensibility (D)—that is, vasoconstriction induced by sympathetic stimulation of the smooth muscle of the peripheral arterial bed. These changes in pulse wave amplitude cannot be the result of changes in carbon dioxide concentration, because the capnogram was maintained steady in all our studies. Peripheral vasoconstriction was recorded during several periods of surgery, but we have established that there is variation between different regions of the body, for instance between finger and pinna, as will be reported in the following

paper.

In the course of an anaesthetic, a gradual but pronounced decrease of the amplitude of the finger plethysmogram is often found. There is a widespread belief that this vasoconstriction is the result of cooling of the skin when exposed to the comparatively cool surrounding temperature in the operating theatre (Otteni, Sauvage and Gauthier-Lafaye, 1971). However, in studying 40 patients in whom skin temperature was measured during anaesthesia, we have found (fig. 6) that the decrease in amplitude always preceded the decrease in finger temperature (Dorlas, 1974; Nijboer, Dorlas and Prins, 1983). Therefore, the decrease in finger temperature is the result of and not the reason for, the vasoconstriction.

In vascular beds which are known to react markedly to stimuli, the responses can be inhibited by certain anaesthetic techniques or sympatholytic agents. Since, in these cases, the walls of the arterial blood vessels are more distensible, the amplitude of the plethysmogram will remain or become relatively large as a sign of vasodilatation and the amplitude will respond mainly to changes in pulse pressure. This is generally noted under neurolept anaesthesia (Buhr and Henschel, 1966), "stress-free" anaesthesia (Savege, 1978) and a high concentration of halothane (Beddard, 1965; Johnstone, 1956). Sporadically, there has been recorded during surgery a sudden increase in amplitude of the finger or ear plethysmogram, or both, which was so large that it could hardly be explained by neurogenic vasodilatation, and other causes such as an increase in pulse pressure or carbon dioxide concentration could be excluded (fig. 7). This phenomenon most often subsided in 5–10 min, and we believe that it has a humoral origin, elicited by release of some vasoactive agent.
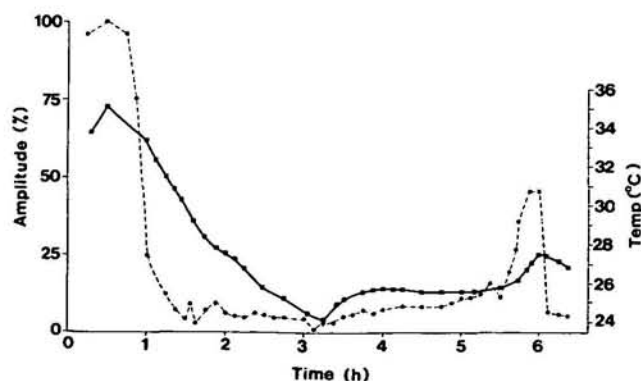

FIG. 6. Illustration of the changes in plethysmographic amplitude (●---●) preceding the changes in skin temperature (■——■) when recorded simultaneously from a finger during surgery.
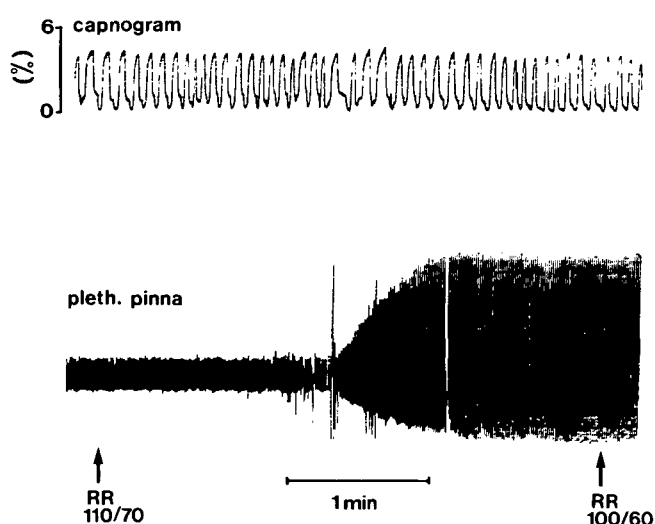
FIG. 7. Sudden, large increase in plethysmographic amplitude in a spontaneously breathing patient during surgery under general anaesthesia. The continuously recorded capnogram and the intermittently measured arterial pressure remain virtually unchanged.

EFFECTS OF THE OPTICAL PRINCIPLE

In addition to the physiological effects, factors which are connected with the optical principle of the method may influence the interpretation of the plethysmogram. Since the amplitude of the arterial pulsations is proportional to the total amount of light detected, it will also depend on the optical density of the tissues surrounding the arterial vasculature. The latter may be influenced by the pressure exerted on the skin by the transducer (Nieveen, v.d. Slikke and Reichert, 1956). De Pater, van den Berg and Bueno (1962) showed that the amplitude increased when the application pressure was increased, and that the amplitude reached its maximum at an application pressure of about 40 mm Hg. Johnstone (1976) suggested that the transducer be replaced every 20 min, because the local pressure on the finger vessels would, in his opinion, result in a gradual decrease in amplitude. This view conflicts with our own that, during the course of an anaesthetic, the amplitude of the finger plethysmogram often varies in an irregular pattern and may even increase. Moreover, these changes in amplitude correlate well with simultaneously-recorded changes in pulse wave amplitude of the mercury-in-rubber strain-gauge which, in our studies, exerted hardly any pressure on the skin of the finger tip. Therefore, we feel that the transducer should not be replaced during one continuous measurement, unless it is realized that a new situation is created in another part of the vascu-

lar bed, or by a change in application pressure.

The total amount of light detected by the photocell may also be altered by venous engorgement. Figure 8 shows that the amplitude of the continuously-recorded ear plethysmogram decreases abruptly when the patient is put in the Trendelenburg position and vice versa. Since no changes were noticed in the other variables, we have attributed these effects to the changes in the amount of venous blood affecting the optical density of the surrounding tissues and not to a change in the actual arterial pulsations.
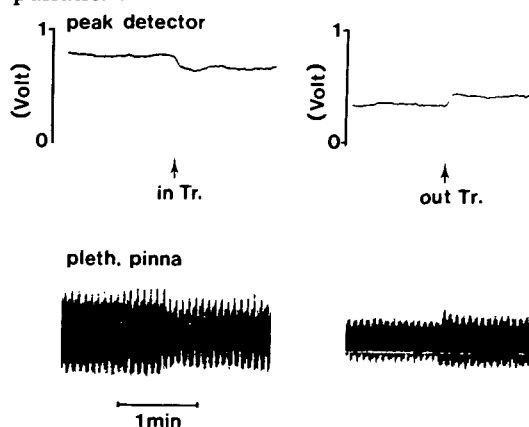

FIG. 8. "Artificial" changes in arterial pulse amplitude when a patient is placed in the Trendelenburg position (in Tr.), and another patient is replaced in the horizontal position (out Tr.).
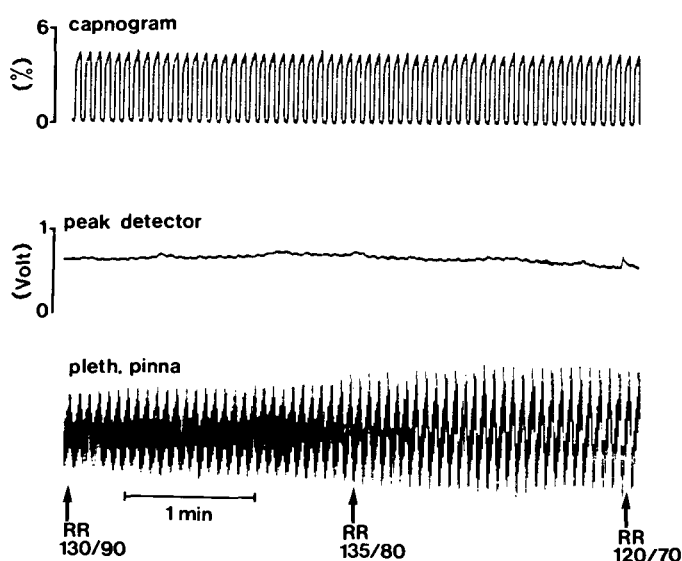
FIG. 9. Increase in height of the ventilatory waves as a result of the development of hypovolaemia, independent of eventual changes in arterial pulse amplitude, capnogram or arterial pressure.

Venous engorgement in combination with application pressure may even give rise to an inverted waveform in the reflection plethysmogram (Nijboer and Dorlas, 1982). This may happen, for instance, during arterial pressure measurement at the same arm, if the cuff is slowly deflated.

VENTILATORY WAVES

Changes in the ventilatory waves may have diagnostic significance. Their height depends mainly on the relationship between central venous pressure and the variations in intrathoracic pressure caused by ventilation, but to what degree these pressure variations are reflected in the plethysmogram also depends on the distensibility of the venous walls. The latter depends substantially on the degree of stretch caused by local venous pressure. Since this pressure decreases in association with hypovolaemia, the distensibility of the walls will increase and the height of the ventilatory waves will increase despite unchanged ventilation pressures. This may happen independently from eventual changes in arterial pulse amplitude or expiratory carbon dioxide concentration (fig. 9). On account of these considerations, an increase in ventilatory waves arising during an anaesthetic with unchanged ventilation pressures is interpreted in our department as a sign of (relative) hypovolaemia.

In conclusion, photo-electric plethysmography is a simple monitoring technique which demonstrates arterial blood volume pulsations, generally superimposed on slower ventilatory waves. Changes in the arterial pulse amplitude during anaesthesia depend mainly on neurogenic or humorally-determined changes in distensibility of the arterial walls, and sometimes on changes in pulse pressure. An increase in the height of the ventilatory waves may be a sign of (relative) hypovolaemia. For the assessment of changes in the plethysmogram, the transducer should not be replaced during one continuous recording. From the optical point of view, the application pressure and the degree of venous engorgement are of importance.

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