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Criteria for Set Point Estimation in the Volume Clamp Method of Blood Pressure Measurement

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Summary

When blood pressure is measured in the finger using the volume clamp method the value at which the vascular volume is clamped is of crucial importance. Since the discovery of the method, several criteria of finding a correct set point have been elaborated: 1. The volume oscillations reach their maximum amplitude at cuff pressure equalling mean blood pressure. 2. The form of the diastolic portion of volume pulsations changes if the cuff pressure moves around the mean blood pressure. 3. The set point can be positioned at one third of the arterial volume. 4. The dynamic vascular compliance (DVC) may be continuously measured as the instantaneous amplitude of vascular volume oscillations is elicited by a relatively small and rapid vibration of the cuff pressure. The shape of the DVC pulse characteristically depends on the transmural pressure (TP): at negative TP (cuff pressure exceeding the blood pressure) it shows a distinct positive systolic peak, at positive TP the polarity of the DVC pulse is reversed. In contrast to the first three ways to find the set point, the last one may operate even in closed-loop performance, i.e. during the blood pressure measurement.

Key words
Blood pressure determination – Methods – Monitors – Vascular unloading technique

About 20 years ago a new principle of indirect continuous measurement of blood pressure was described (Peňáz 1969, 1973). It is based on clamping the volume of finger arteries by fast changes of pressure in a special cuff equipped with a photoelectric plethysmograph to measure the vascular volume. The system performs in two ways (Fig. 1): in open-loop operation (preparatory phase) the cuff pressure is set to a constant level and the vascular volume oscillates according to fluctuations of the transmural pressure (TP – equalling intraarterial minus cuff pressure), in closed-loop operation (measurement of blood pressure), the vascular volume itself controls the cuff pressure in such a way that any potential change of volume is instantaneously compensated by a corresponding change of cuff pressure so that the arterial volume is fixed (clamped) at a constant value. Under certain conditions, one of them being complete unloading of the arterial wall, the cuff pressure corresponds to the intraarterial pressure and quantitatively describes its full wave form.

The feedback circuits providing this function can be set to clamp the vascular volume at any desired value. The value chosen or the s.-c. set point is of crucial importance for the recorded pressure to be identical with the arterial pressure. Fig. 2 shows the effect of a set point shift in the whole range which is technically possible. The record was obtained in the following way: an external ramp voltage was introduced, by means of a summing element, into the servoloop causing a slow linear decrease of the clamped vascular volume ("volume ramp") from normal uncompressed state to the point where all blood was expelled so that no further vascular compression is possible. Disregarding its final steep rise, the cuff pressure increases in two separate phases obviously corresponding to compression of the venous and the arterial sections, respectively. The arterial section of the pressure curve shows a certain plateau in the middle of which one can presume a point (arrow in Fig. 2) where the cuff pressure should correspond to the arterial pressure. Since the plateau is not horizontal, it is obvious that a correct pressure recording is only possible at one distinct value of the clamped vascular volume.

Finding this value, i.e. estimating a correct set point of the volume clamping servosystem is, therefore, the first and indispensable task of any instrument using this principle.

Initial value of set point and its spontaneous change

Early experiments with instruments of this kind brought a surprising observation that even when a correct set point was chosen at the start, the recorded pressure often showed a gradual decrease although no such decline was observed in the intraarterial pressure recording (Molhoek *et al.* 1984). The phenomenon occurs mainly in the first minutes after the feedback had been closed. If the set point is reestimated, the clamped vascular volume is slightly lower. The gradual decrease of the set point has an exponential course becoming unimportant after 10 to 60 minutes. Sometimes, however, the set point may shift even after this time and in both directions.

The cause of the set point shift is not clear enough. First, it may reside in a gradual change of the arterial wall tension. If the arterial smooth muscle increases its tonus, then the volume of the artery under zero transmural pressure tends to decrease, but since the volume is clamped at its original value by action of the servosystem, the cuff pressure sinks below the level of arterial pressure. If the set point is reestimated in this phase, a lower value is found. The above mentioned increase of set point value may be explained in a similar way.

The initial decrease of the recorded pressure or of the set point value may be due, however, to quite a different mechanism, i.e. to a gradual expulsion of blood from the incompletely compressed non-arterial vessels, probably capillaries. Some blood may have remained in these vessels after the initial cuff pressure rise and may have been drained away only slowly during the pressure measurement. Since the photoelectric plethysmograph measures the amount of blood in all vessels, this situation leads to the same change of cuff pressure as if arterial tonus had increased.

The third explanation of this phenomenon takes into account that a prolonged reduction of effective vascular pressure under the cuff might reduce tissue fluid volume. This would lead to changes in the finger dimension approaching thus the photoelectric elements which could simulate decreased opacity.

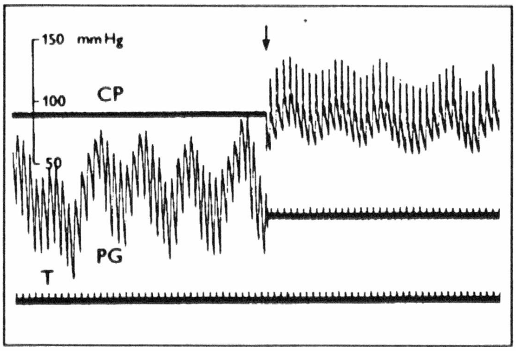

Fig. 1
Left part: open-loop performance. Plethysmogram (PG) at constant cuff pressure (CP). Right part: closed-loop performance. Arrow – closing the feedback; plethysmogram "clamped" at constant value, cuff pressure describes blood pressure.

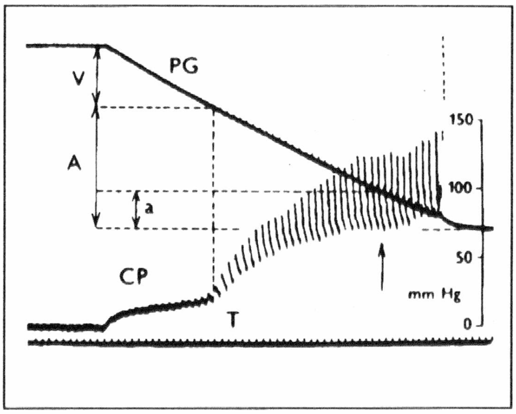

Fig. 2
Volume ramp: PG – plethysmogram, V – venous, A – arterial section of vascular volume, CP – cuff pressure, T – time in s, a – one third of arterial volume. Arrow – presumably correct position of set point

It is probable that all these mechanisms take part in the observed changes of the set point value. At any rate, an adequate set point should not only be found initially in the volume clamp technique, but also corrected during the further phase of the measurement.

In the following text, four different ways of finding or correcting the set point will be described.

Principle of maximum pulsations

If the cuff pressure is changed in the open-loop performance, the volume pulsations recorded by the photoelectric plethysmograph change their amplitude: at low pressure they are small, with increasing pressure their amplitude rises to reach a maximum at cuff pressure equalling mean blood pressure. Then the pulsations decrease and disappear at cuff pressure slightly exceeding the systolic pressure. Marey (1885) was the first to observe this phenomenon which is now widely used in oscillometric methods of measuring blood pressure.

In connection with the volume clamp method, the principle may be applied as follows: in open-loop performance, the cuff pressure is raised either gradually or in small steps and the amplitude of plethysmographic pulses is measured and memorized. The cuff pressure is then returned to that value where the volume pulses had attained their maximal amplitude, the average d.c. value of the plethysmogram is taken as the set point and the servoloop is closed (Boehmer 1987, Yamakoshi *et al.* 1980). The optimal loop gain may also be set according to the amplitude of maximal volume pulses.

Shape of volume pulse

In open-loop performance, not only the amplitude, but also the shape of volume pulsations changes characteristically with the ranges of cuff pressure. At values below the mean blood pressure, the plethysmogram shows "round", "full" pulse waves the katacrotic part of which is convex. As cuff pressure rises above mean blood pressure, the katacrotic section becomes concave and its last part acquires an almost horizontal course (Fig. 3). Wesseling (1985) was the first to use this phenomenon in a microcomputer program to find and to correct the set point in his development of the volume clamp system: in his "Finapres" (finger arterial pressure) the procedure was called "Physiocal" (physiological calibration).

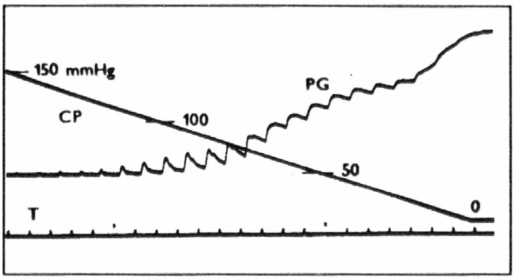

Fig. 3
Wave form changes of plethysmogram (PG) during linear decrease of cuff pressure (CP). T – time in seconds

The procedure is especially appropriate for a fast set point correction, i.e. for a periodic compensation of the spontaneous set point shift. It works as follows: blood pressure recording is interrupted for 2 or 3 pulse intervals by opening the servoloop. Cuff pressure is then set at 2 or 3 values slightly above and below the measured mean blood pressure and the respective plethysmographic waves are recorded. Their diastolic part is evaluated and the necessary correction of the set point calculated. With the new value of the set point the servoloop is closed again.

The procedure was tested in numerous comparative studies including various clinical conditions (e.g. Epstein *et al.* 1989, 1991, Gorback *et al.* 1991, Kurki *et al.* 1987, Molhoek *et al.* 1984, Smith at al. 1985). The tests proved that the blood pressure recorded by this procedure does not considerably differ from the intraarterial pressure. The accuracy is about the same as by other indirect methods.

The only disadvantage of this method consists in the fact that the pressure recording must be interrupted periodically for 2 or 3 cardiac intervals which may bring some problems where longer continuous pressure recordings are needed (e.g. for spectral analysis). In commercially available instruments (Finapres – Ohmeda) the periodical corrections may be switched off.

Principle of one third arterial volume

In the first publication on the volume clamp method (Peňáz 1973), it was stated that the adequate set point lies in about one third to one quarter of volume of the arterial section. The very first plethysmogram at linearly rising cuff pressure was also shown in that paper – a procedure later called "pressure ramp". The photoelectric volume drops rapidly at cuff pressure rising from 0 to about 4 kPa (30 mmHg), then the decrease suddenly stops to be followed by another decline which is S-shaped and slower than the first one (Fig. 4). The initial fast decrease is obviously caused by the expulsion of blood from the low pressure system of the finger, the remaining slower part of the curve depicts gradual emptying of arterial vessels. The S-shaped part may thus be considered as a sort of arterial pressure-volume diagram.

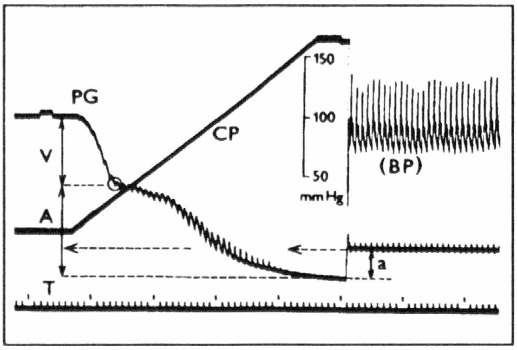

Fig. 4
Left: pressure ramp. Right: one third principle. PG – plethysmogram, CP – cuff pressure, BP – blood pressure, A – arterial section, a – one third of its volume, V – venous or low pressure section, circle – inflection point as margin between arterial and venous section

For set point estimation it is, of course, not necessary to know the whole course of the diagram but only its start and end points. To provide some reserve for patients with increased venous pressure, these points may be set at 5.5 kPa (40 mmHg) and at a pressure surely exceeding systolic pressure, for normotensive subjects e.g. 26 kPa (200 mmHg). The procedure is illustrated in Fig. 4.

For set point correction, it is not necessary to repeat the whole algorithm; one can use the old value obtained at lower pressure and measure the new value at suprasystolic pressure only. This shortens the time needed to about 6 s. At any rate, however, this process again means an interruption of the continuous measurement with the drawbacks mentioned above.

Measurement of instantaneous vascular compliance

A few years ago, a way was found to correct the set point continuously, i.e. during the pressure measurement, without any interruption. The new principle (Peňáz 1989, 1990) uses small pressure vibrations of a relatively high frequency (above the frequency of important harmonics of the pulse wave) which are superimposed on the cuff pressure. The vibrations bring about similar oscillations in the photoelectric plethysmogram that are superimposed upon the pulse wave deflections. In open-loop performance, it is seen that the amplitude of volume oscillations depends on the arterial wall tension: at zero tension, it is maximal, at its positive or negative deviations it is smaller. In other words, volume oscillations are maximal if cuff pressure equals the intraarterial pressure, i.e. at zero transmural pressure and decrease both at positive and negative transmural pressure.

The principle has been employed in a new blood pressure measuring instrument. In this instrument, 50 Hz pressure vibration is added to the cuff pressure in closed-loop performance, i.e. during the measurement of blood pressure. The 50 Hz volume oscillations (Fig. 5) are isolated, amplified and detected; the resulting curve depicting the amplitude of volume oscillations may be considered, since amplitude of the pressure vibration is constant, as changes of instantaneous or dynamic vascular compliance (DVC). The shape and polarity of the DVC pulse depend on the set point (Fig. 5): if the clamped vascular volume is too large (and hence the recorded pressure too low), the DVC curve has a negative systolic deflection; if the set point is too low (and the recorded pressure incorrectly high), the DVC shows a clear-cut positive systolic peak.

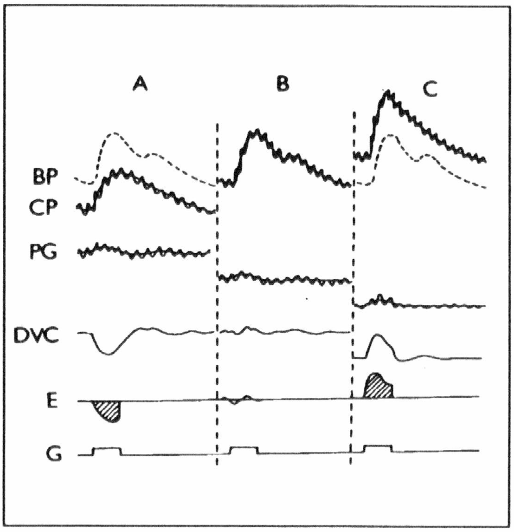

Fig. 5
BP – Blood pressure (intraarterial), CP – cuff pressure with superimposed vibrations, PG – plethysmogram, DVC – dynamic vascular compliance, E – error signal, G – gating voltage. Recorded pressure lower than (A), equal to (B) and higher than (C) intraarterial pressure.

The method has, however, some inherent disadvantages. First, the loop gain cannot be set as high as is usual in modern versions of the volume clamp method. For detecting a change in the DVC, a certain value of rest error (a small systolic deflection despite volume clamping) must be allowed by setting the gain slightly below its optimal level. And second, the 50 Hz oscillation must be filtered out in certain circuits of the system which impairs its overall frequency response.

Concluding this paragraph, it should be noted that the described method is, strictly speaking, no more a "volume clamp" method since the "clamped" vascular volume continuously changes. A designation "floating set point" should perhaps be more adequate.

Conclusion

From the above four methods of set point estimation, the first two have been embodied into the commercial instrument Finapres TM 2300 – Ohmeda. The first one is used in the USM-801 Continuous Blood Pressure Instrument – Ueda, Japan. Comparative studies showed that the volume clamp methods using maximum pulsation and pulse form criteria are at least as accurate as other indirect methods of blood pressure measurement. Instruments using the remaining two criteria are not yet commercially available and have not yet been tested in this way. A comparison with instruments of the Finapres type showed, however, that even these criteria provide reliable blood pressure values.

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Reprint Requests

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