Appendix A

Continuous noninvasive blood-pressure measurement according to Penaz

A.1 Introduction
Both physiologists who study the human cardiovascular system and clinicians are longing for an instrument that allows reliable, non-invasive, continuous measurement of blood pressure. Several instruments are now available that measure systolic and diastolic pressures automatically, using a cuff around the upper-arm (e.g. Arteriosonde). The interval between successive measurements is of the order of a minute. However, these instruments do not meet the needs if a continuous registration is needed for research purposes or in an intensive-care unit.

In a contribution to the 10th International Conference on Medical and Biological Engineering (1973, Dresden) Dr.J.Penaz described an instrument for the continuous measurement of blood pressure, using the principle of the "unloaded vascular wall". Essentially, the pressure of an inflatable cuff around a finger is continuously adjusted so as to maintain the vascular volume at its unloaded, hence constant, value. Under these "volume-clamp" conditions, the cuff pressure equals the arterial blood pressure. The vascular volume is monitored by a small lamp and a photocell on either side of the finger; the output of the photocell is used to adjust the cuff pressure. An important improvement of Dr. Penaz' approach over previous ones is the use of a feedback loop to control the vascular volume.

Ir.K.H.Wesseling and coworkers of the "Research Unit Biomedical Instrumentation" (TNO) developed this instrument further and made it suitable for clinical use (Fin.A.Press; Molhoek et al., 1983; Wesseling et al., 1982, 1985; Settels and Wesseling, 1985). Some of the blood pressure recordings used in this study were obtained with prototypes of this instrument and therefore it seemed appropriate to include at this place a description of the instrument.

In our opinion, the original 1973 paper of Dr.Penaz gives the most lucid explanation of the principles involved in the working of the instrument; however, this paper is not easily accessible and therefore we decided to reproduce it here in full. We are grateful to Dr.Penaz and to the copyright holder for permission to do so.

One remark: the "waves" in fig.3 of Dr.Penaz' paper are neither respiratory waves nor due to the 10-second-rhythm: they originate from a voluntary up-and-down movement of the arm (Dr.J.Penaz, personal communication).
SESSION 7  Haemodynamics I

7-2 PHOTOELECTRIC MEASUREMENT OF BLOOD PRESSURE, VOLUME AND FLOW IN THE FINGER

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PROBLEM. Methods of indirect continuous measurement of blood pressure using the principle of the "unload­ed vascular wall" have not been satisfactorily de­veloped as yet. In the system presented here, some drawbacks of the former methods were avoided by the use of a feedback system maintaining constant vas­cular volume. The new system can also be used for other vascular measurements.

PRINCIPLE OF THE METHOD is shown in Fig.1. Its basic part is a photoelectric plethysmograph equipped with a transparent inflatable cuff (S) the pressure within which is controlled by an electro-pneumatic sys­tem (PA, EPT). Open- or closed-loop operation may be chosen by the switch SW, the instrument performing thus plethysmographic or pressure measurements, respectively.

Fig.1. Block diagram of the system. F - finger, L - lamp, PC - photocell, S - segments of transparent pressure cuff, DA - difference amplifier, PID - correcting network, PA - power ampli­fier, EPT - electro-pneumatic transducer.
A. PLETHYSMOGRAPHY AT CONTROLLED PRESSURE. In open-loop performance (SW on), the photoelectric plethysmogram (PG) is recorded at cuff pressure (CP) which is either set at a fixed value or changed by means of an external electric signal (C2). If the cuff pressure is gradually increased or decreased, the vascular volume changes in a characteristic way (Fig. 2). From the graph, volumes of the total vascular bed and of its two compartments may be easily estimated. Accordingly, the plethysmogram recorded at the constant pressure of about 40 mm Hg may reflect responses of the arterial compartment only.

If short pressure pulses synchronized by the cardiac rhythm are applied, the system measures the instantaneous finger blood flow. Each pressure pulse expels blood from the venous compartment which is then gradually refilled from the arterial side. The differential quotient of the plethysmogram during the refilling phase is a direct measure of the arterial inflow.

![Diagram](image)

Fig. 2. Plethysmogram (PG) during linear increase of cuff pressure (CP).
B. RECORDING OF BLOOD PRESSURE. In this case, the cuff pressure is controlled by the plethysmographic signal (closed-loop operation) so that the vascular volume is "clamped" to a pre-set value. Before closing the control loop, the cuff pressure is raised as much as the arterial compartment is compressed to about one third of its normal volume ("unloading"). After compensation of the plethysmographic signal \( G_1 \) - Fig. 1, the control loop is closed (SW off). From this moment (Fig. 3), any deviations of vascular volume due to changes of intravascular pressure are instantaneously compensated by automatic adjustment of the cuff pressure which thus continuously and quantitatively follows the intravascular pressure.

![Diagram](image)

Fig. 3. Left: Plethysmogram (PG) at constant cuff pressure (CP). Right: Record of blood pressure.

DISCUSSION. Advantages of the system performing several non-invasive vascular measurements are obvious. The indirect measurement of blood pressure seems to be the simplest and the most versatile method of this type described until now. Its disadvantage is the possibility of a difference between the peripheral and the central blood pressure.