Noninvasive automatic monitoring of instantaneous arterial blood pressure using the vascular unloading technique

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Abstract—For the noninvasive monitoring of the beat-to-beat systolic and diastolic pressure and pressure waveform in the human finger, a new automated instrument was designed. This measurement is based on a principle called the vascular unloading technique. Using a hydraulic servocontrol system, the vascular volume change caused by intra-arterial pressure change can be compensated by applying counter pressure to maintain a constant vascular volume in the unloaded state. In this state the controlled counterpressure instantaneously follows the intra-arterial pressure. In this instrument all the necessary procedures, such as the setting of the reference value for the servocontrol, control of the servogain, processing and displaying of the data on a recorder, were carried out automatically. The simultaneous comparison of data with direct measurements and a few examples of the indirect pressure recordings by this instrument are shown and the principles, operation and evaluation of this method are described. This instrument was shown to permit the noninvasive and accurate tracking of instantaneous arterial pressure and to perform acceptably over a wide range of arterial pressure.

Keywords—Instantaneous arterial pressure, Noninvasive automatic monitoring, Servocontrol system, Vascular unloading technique

1 Introduction
Various automatic instruments for the noninvasive measurement of arterial blood pressure have been developed (GEDDES, 1970; COBBOLD, 1974). In most of them the sphygmomanometric technique based on Riva-Rocci's principle is utilised, so that the arterial pressure can be monitored only intermittently. Since then, much effort has been expended in devising noninvasive methods such as arterial tonometry (SMITH and BICKLEY, 1964; PRESSMAN and NEWGARD, 1963; STEIN and BLICK, 1971) and the tracking-cuff method (SHAPIRO et al., 1981) for the beat-to-beat continuous recording of arterial pressure. However, because there are some practical and/or seriously unsolved problems in the measurement principle (YAMAKOSHI et al., 1980; SHAPIRO et al., 1981), the progress in these methods has not yet been extended so as to be in wide use.

We have recently devised a new method for the noninvasive measurement of beat-to-beat systolic and diastolic pressure and pressure waveform, and demonstrated its validity and accuracy through in vitro and in vivo studies using excised arterial segments, the rat's tail and the human finger (YAMAKOSHI et al., 1979, 1980). This method is based on a principle known as the 'indirect unloading technique' which was originally proposed by MAREY (1876) (GEDDES, 1970) and lately by SHIRER (1962) and PENAZ (1973). Using a hydraulic servocontrol system, the vascular volume change associated with intra-arterial pressure can be compensated by applying counter pressure to maintain a constant vascular volume in an unloaded state. The vascular volume in this state is called the unloaded vascular volume. In this state the controlled counter pressure instantaneously follows the intra-arterial pressure.

This paper describes a new automated instrument using this technique, which was designed for practical and convenient use for monitoring the instantaneous arterial pressure continuously and noninvasively. The simultaneous comparison of data with direct...
measurements and a few examples of the indirect pressure recordings by this instrument are shown and the operation and evaluation of this instrument are described.

2 Materials and methods

2.1 Description of the instrument

2.1.1 Servocontrol system and mechanical and volume-sensing units. Fig. 1 is a schematic diagram of the instrument for the automatic measurement of instantaneous arterial pressure at the middle or root of a human finger. The principle of this instrument is based on the volume-servocontrol system which is essentially the same as that previously reported (Yamakoshi et al., 1979, 1980). The major components of this instrument are:

(a) a hydraulic compression chamber which is equipped with an occluding cuff
(b) an electromagnetic shaker for controlling the counter pressure (cuff pressure \( P_c \))
(c) an infra-red transmittance photoelectric plethysmograph
(d) a volume servo circuit
(e) a pen recorder
(f) a processing unit which operates a sequential control of the entire measurement procedure.

The chamber has a diaphragm actuator (effective diaphragm area = 15 cm\(^2\)) which is linked with plunger (\( p \)) of the shaker via a retainer plate (r.p.) firmly fixed to the diaphragm. A finger is placed in the chamber through the cuff, so that the finger segment can be compressed by the hydraulic pressure in the chamber (\( P_c \)). The cuff is a thin-walled (0.1 mm) rubber tube which is formed so that no cuff tension is developed during the compression. Both flanges of the cuff are firmly fixed to both ends of the chamber by a pair of annular discs (a.d.). The effective cuff widths used were 22, 26 and 30 mm, with respective inner diameters of 15, 20 and 23 mm, according to the size of the finger segment. This mechanical chamber system has a compliance of approximately 0.2 ml/100 mm Hg.

The shaker (G-005, Shinken Co.) has a maximum displacement of \( \pm 5 \) mm, a force of 68.7 N and a natural frequency of 90 Hz. The position of the plunger is sensed by a photoelectric linear displacement transducer (l.t.) (frequency response \(-3 \) dB at 100 Hz). The controlled volume \( S_c \) can be obtained if necessary from the output of this transducer. The cuff pressure is measured by a pressure transducer (UPS-300, Ueda Electronics Works Co.; linearity 0–300 mm Hg/\( \pm 0.1 \% \) full scale, frequency response, flat up to about 80 Hz).

The photoelectric plethysmograph is used to detect the volume change in the finger. Series-connected light-emitting diodes (TLN 104, Toshiba Electric Co.; peak wavelength, 940 nm) and parallel-connected phototransistors (TPS 605, Toshiba Electric Co.) serve

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**Fig. 1** Schematic diagram of the instrument for the noninvasive measurement of instantaneous arterial pressure in the finger. The solid thick line indicates the volume servo-control loop. The arrangements and connections of the light-emitting diodes (l.e.d.) and the phototransistors (p.t.) are shown in the insets. For symbols see text.