TONOMETRY, ARTERIAL

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INTRODUCTION

The arterial tonometer is an instrument for measuring arterial blood pressure. It differs from the familiar sphygmomanometer in that, rather than measuring the pressure only at greatest contraction and greatest heart dilation (systolic and diastolic), it provides continuous measurement throughout the heart's pumping cycle. Typically, the instrument sensor is placed over a superficial artery; the radial artery pulse point at the wrist is one convenient site for tonometer measurements. Figure 1 shows how a tonometer sensor would be placed for measurements at this site.

A catheter can be used for accurate, continuous measurement of blood pressure, but the instrument is invasive and numerous risks are associated with its use. In contrast, the noninvasive tonometer can provide an accurate, continuous blood pressure measurement with negligible risk.

Sphygmomanometric instruments of several types are available for noninvasive blood pressure measurements. However, these instruments are generally not capable of continuous blood pressure measurement, nor is their long-term use feasible. The familiar blood pressure cuff hinders venous return and results in peripheral edema. In contrast to sphygmomanometric instruments, the tonometer can be used for beat-by-beat blood pressure measurement over long periods of time with minimal edema. Important disadvantages of the tonometer include its sensitivity to sensor placement and movement artifacts, effects of anatomical variations, and the greater complexity and cost relative to a conventional sphygmomanometer.

In what follows, the physical principles that form the theoretical basis for tonometric blood pressure measurement are first presented; these include techniques for identifying the location of an artery beneath a tonometer sensor and for adjusting the force with which the sensor is pressed against the skin. Next, the technical evolution of tonometer transducers is discussed, leading to a description of modern, multiple-element transducers. This is followed by discussion of several considerations that are unique to tonometric measurements, and may influence the usefulness of the technique for certain applications. Various applications of tonometry, particularly surgical monitoring and cardiovascular evaluation, are discussed next. Finally, the measurement accuracy of tonometry is addressed.

PRINCIPLES OF OPERATION

General Principles

The fundamental principles underlying arterial tonometry are similar to those for ocular tonometry (1,2). Figure 2 shows an idealized model that helps illustrate these principles. In Figure 2, P represents the blood pressure in a superficial artery and F is the force measured by a tonometer transducer. The membrane is the artery wall. Figure 2b is a "free body diagram" showing all the forces and moments acting on the frictionless piston of Fig. 2a. As shown in Fig. 2b, an ideal membrane transmits only a tensile force, T, and does not transmit any bending moment. The tension vector shown, T, is perpendicular to the pressure vector, so the force, F, is independent of T and depends only on the blood pressure and the area of the frictionless piston, A. Following common practice, the integrated effect of arterial pressure acting on the segment of arterial wall is represented by a vector of magnitude PA, oriented perpendicular to the wall. Thus, measurement of the force, F, permits one to directly infer the intraarterial pressure.

Figure 3 shows a superficial artery and a tonometer sensor in cross-section. The tonometer sensor is represented schematically, and is modeled as an assemblage of springs with spring constants, K, as shown. By careful design of the tonometer sensor and selection of an appropriate superficial artery, it is possible to satisfy several conditions:

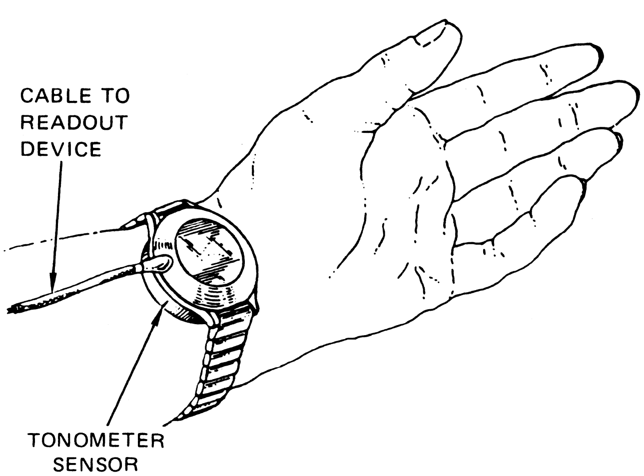

Figure 1. Arterial tonometer sensor on radial artery.

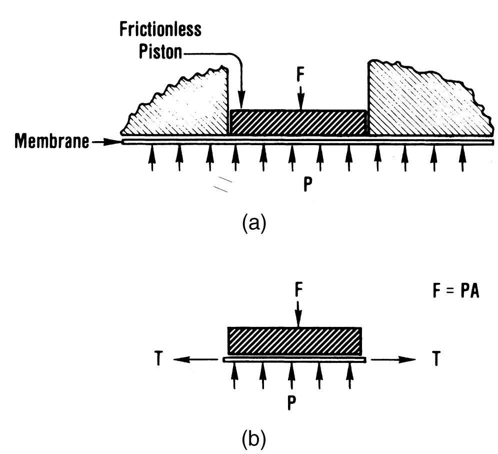

Figure 2. Idealized model for a tonometer.

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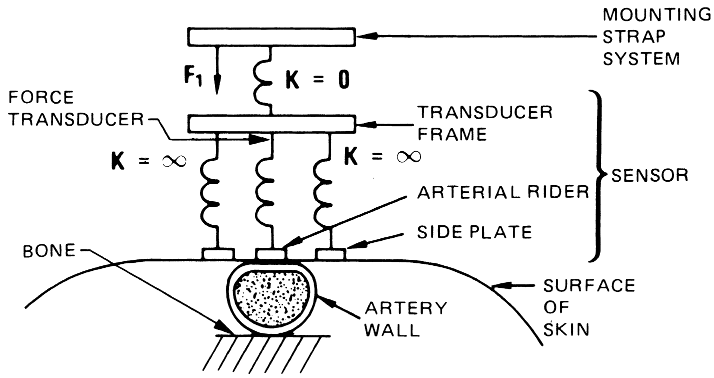

Figure 3. Schematic diagram of a tonometer sensor and a superficial artery.

1. The artery is supported from below by bone (e.g., the radius).
2. The hold-down force, F_1, flattens a portion of the artery wall, but does not occlude the artery.
3. The thickness of the skin over the artery is insignificant, compared to the artery diameter.
4. The artery wall behaves essentially like an ideal membrane.
5. The arterial rider is smaller than the flattened area of the artery, and is centered over the flattened area.
6. The spring constant of the force transducer, K_T, is large compared to the effective spring constant of the artery.

When all these conditions are satisfied, Pressman and Newgard (3) showed theoretically that the conditions of Fig. 2 apply where the arterial rider of Fig. 3 corresponds to the frictionless piston of Fig. 2. Thus, the electrical output signal of the force transducer is directly proportional to the intraarterial blood pressure.

The arterial tonometric measurement depends on the membranelike behavior of the artery wall. Drzewiecki et al. (4) have shown analytically and by experiments with an excised canine femoral artery (5) that the desired behavior can be obtained, provided that the artery is flattened sufficiently. This work provides an important theoretical foundation for the arterial tonometer and helps to explain the observations of several prior *in vivo* studies.

Multiple-Element Sensors

A major practical problem with the simple arterial tonometer of Fig. 3 is the requirement that the arterial rider be precisely placed over the superficial artery. Reliable measurements can be obtained only after painstaking adjustment of the sensor location by a trained operator (6). Apparently, there are differences of opinion concerning the severity of this positioning problem and these are discussed in greater detail below.

To ameliorate this problem, multiple-element tonometer sensors, shown schematically in Fig. 4, have been developed (7–9). The sensor worn by the patient actually consists of a multiplicity of individual sensors. Typically, the sensors are arranged to form a linear array of force transducers and arterial riders. The array need only be positioned with enough precision so that some element of the array is centered over the artery. A computer then automatically selects the sensor element that is correctly positioned over the artery.

One algorithm for selection of the correct element from the multiple-element sensor array exploits two characteristics of the pressure distribution in the vicinity of the artery (8). The first is that the pulse amplitude (i.e., the pressure difference between the systolic and diastolic points on the transducer output waveforms) exhibits a broad maximum over the artery. The algorithm searches for the largest pulse amplitude; the corresponding sensor element will then be within about one artery diameter of the center of the artery. However, this element will, in general, not be precisely centered over the artery.

To identify the centered sensor element more precisely, the algorithm then exploits a second phenomenon, illustrated in Fig. 5. This figure shows a multiple-element tonometer sensor and the underlying, partly compressed artery. For purposes of illustration, assume that the diastolic pressure in the artery is 80 mmHg (10.7 kPa). At the instant of diastole, the pressure measured by each element of the sensor is shown plotted at the top of the figure. Elements 4–6, which all lie over the flattened part of the artery wall, measure the intraarterial pressure [80 mmHg (10.7 kPa)] with good accuracy. However, the pressures measured by elements 2, 3, 7, and 8 are all significantly greater than the intraarterial pressure. This higher pressure can be explained by noting that the artery wall is bent to a very small radius in the regions below the latter elements. As a result, large bending moments are transmitted by the artery wall and are manifested as increased

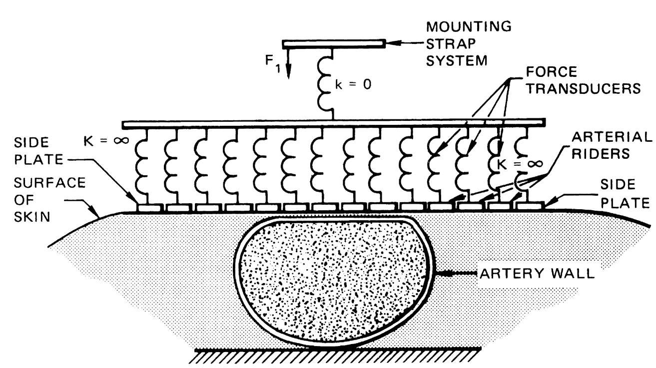

Figure 4. Multiple-element arterial tonometer.

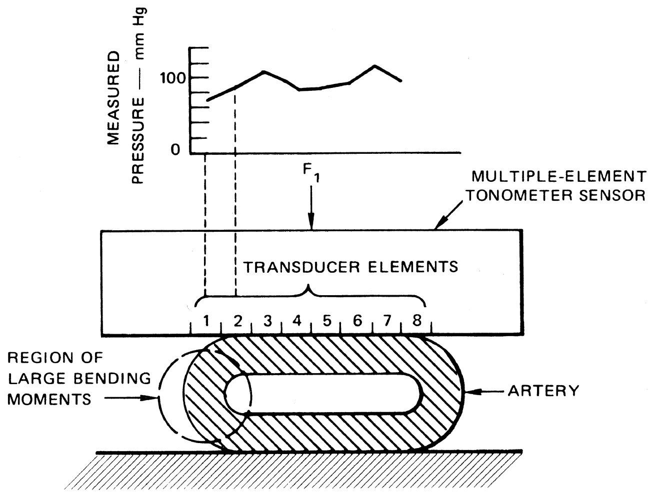

Figure 5. Illustration of pressure distribution near a superficial artery.

pressure on the adjacent sensor elements. A more detailed treatment of this phenomenon can be found in Drzewiecki et al. (4). The element-selection algorithm exploits this phenomenon by searching for a (spatial) local minimum in diastolic pressure (e.g., element 5 of Fig. 5) in a region near the maximum pulse amplitude. The term "local minimum" has a precise meaning in mathematics: When moving in either direction from a local minimum, the value of the function increases. The sensor element corresponding to the local minimum is then assumed to be centered over the artery and blood pressure is measured with this element (10).

Recently, there have been several efforts (11–13) to improve the basic algorithm described above. One algorithm or another might be most effective depending on numerous factors, such as the application, the patient population, and the precision of the sensor and associated amplifiers.

To further ameliorate the positioning problem, Shinoda and others (14,15) have developed motor-driven mechanisms to move a multiple-element sensor laterally within a larger housing strapped to the wrist.

Hold-Down Force

Adjusting the tonometer sensor's transverse location with respect to the artery is not enough; the degree of arterial flattening is also important for accurate tonometric pressure measurement. Arterial flattening depends on the interaction of anatomical factors with the value of the hold-down force, F_1, in Fig. 3. The appropriate value of the hold-down force must be determined for each subject before accurate tonometric measurements can be made. The procedure commonly employed involves increasing (or decreasing) the hold-down force gradually while recording the signal from the tonometer sensor. Figure 6 is an example of such a recording (16). In Fig. 6, hold-down force decreases with time through regions A, B, and C. Region B, where the pulse amplitude is greatest, is considered (3,16,17) to be the region where the most accurate blood pressure measurements are made. This region corresponds to flattening of the artery (as shown in Fig. 5) that is insufficient to cause its occlusion.

Drzewiecki et al. (5) discuss the effects of hold-down force from a theoretical perspective. Eckerle (18) developed algorithms for automatic identification of the center of region B (Fig. 6) and for recognition of difficult subjects (see below) based on various parameters that define this region. Briefly, the algorithm fits a third-order polynomial to the data of Fig. 6. The locations of the regions of Fig. 6 can then be directly computed from the polynomial coefficients. Recently, alternative algorithms (19,20) to control hold-down force have been developed. Again, the optimum algorithm may depend on factors such as application, population, and equipment precision.

TONOMETER SENSOR DESIGN

The size and precision requirements for tonometric blood pressure sensors are severe. Eckerle et al. (21) conclude that, ideally, the arterial rider should be less than ~0.2 mm wide and the associated transducer should be accurate to better than ±2 mmHg (270 Pa). For multiple-element sensors, at least 25 elements with interelement spacings of ~0.2 mm are desirable. As of 1984, these design goals had been approached but not met (21). Then, in 1990, an integrated circuit (IC) based tonometer sensor array was

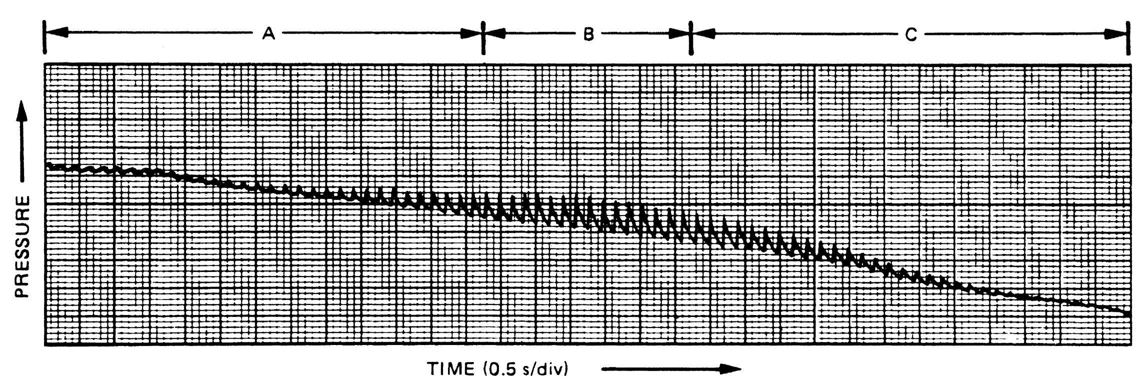

Figure 6. Effect of hold-down force on a tonometer output signal.

reported (9) that substantially achieved these goals. The silicon-and-glass sensor die included 31 tonometer sensor elements in a linear array ~6 mm long.

The first single-element tonometer sensors were constructed of aluminum. Strain gages were attached to miniature beams supporting the arterial rider (3). This approach made effective sensors, but they suffered from the positioning problems previously discussed. Subsequently, various workers devised alternative single-element tonometric sensors. Bigliano et al. (22) reported a pressure sensor with a thin membrane that controlled air flow through a narrow passage. Stein and Blick (23) used a modified myographic force transducer to record blood pressure waveforms from the radial artery. Bahr and Petzke (17,24) used a semiconductor pressure transducer placed over the radial artery. Kelly et al. (6) used a pressure sensor intended for insertion via a catheter. This sensor was mounted in the tip of a pencil-shaped probe, which was then applied to the skin. Borkat et al. (25) placed a pressure capsule, consisting of a rubber bladder attached to a pressure transducer, over the radial artery. Borkat's device is probably the most inexpensive and simple of these alternatives, but it fails to meet the size and stiffness requirements that apply for accurate tonometric measurements.

Multiple-element tonometer sensors have been fabricated from a monolithic silicon substrate using anisotropic etching to define pressure-sensing diaphragms about 10 μm thick in the silicon (26). The IC processing techniques are then used to create piezoresistive strain gages in the diaphragms. External circuitry measures the resistance of the strain gages to determine the pressure exerted on each sensor element. Figure 7 is a photomicrograph of an eight-element sensor fabricated in this way. The diaphragms are square and are arranged in two staggered rows of four each. Note the scale in the figure. The arterial riders in this device are 0.75×0.75 mm. Figure 8 is a further magnified view of one element of the Figure 7 sensor. Two radial and two tangential piezoresistive strain gages can be seen together with aluminum metallization used for connection to external circuitry. The performance of these sensors is representative of the best that had been achieved (for tonometers) as of 1984 (21) and is summarized in Table 1.

Achieving the size and accuracy requirements for multiple-element tonometer sensors noted above (21) is difficult, even using the latest advances in IC sensor fabrication. One fundamental problem involves the difficulty of placing independent pressure sensors side by side while minimizing interaction between them. In 1990, Terry et al. (9) reported a clever configuration to address this problem. Briefly, a multiplicity of independent pressure transducers shared a single, long, narrow silicon diaphragm. Some performance parameters of this sensor are also shown in Table 1. This sensor was the first to substantially achieve the size and precision requirements proposed by Eckerle et al. (21).

While the single-diaphragm sensor of Terry et al. (9) has superior performance, relative to the Fig. 7 device, it requires a more complex manufacturing process, and is therefore more expensive. For cost-sensitive applications, a sensor such as Fig. 7 may be preferred. Other groups are investigating fiber-optic transducers (27) and capacitive transducers (28,29) for use in multiple-element tonometer sensors.

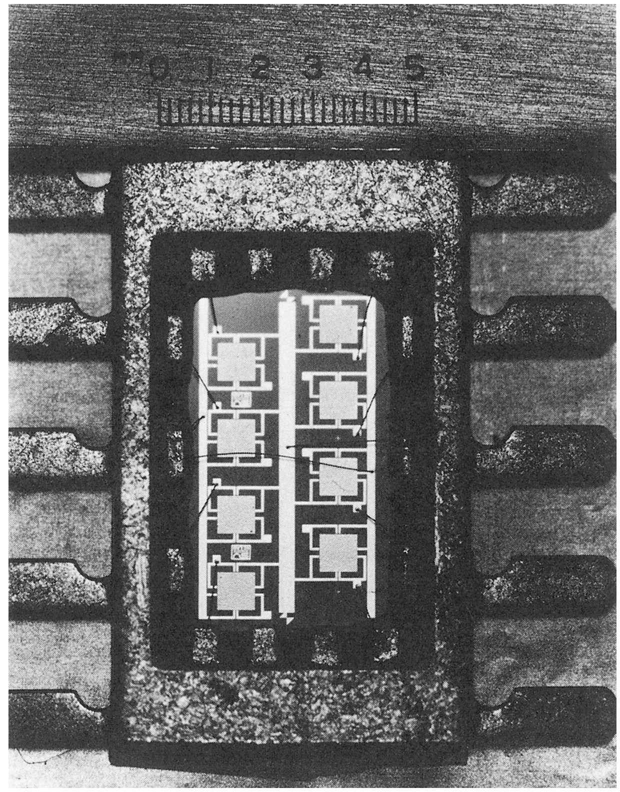

Figure 7. Eight-element tonometer sensor.

Proper mounting of an IC tonometer sensor is very important. The mounting arrangement must protect the fragile sensor while faithfully transmitting the pressure of the patient's skin to the sensor. Consideration should be given to measurement drift caused by thermal effects or material creep. Finally, the shape of the mounted sensor can be chosen to conform to the local anatomy (e.g., the nearby radius in the case of a radial artery tonometer). Fujikawa and Harada (30) and others (31,32) developed

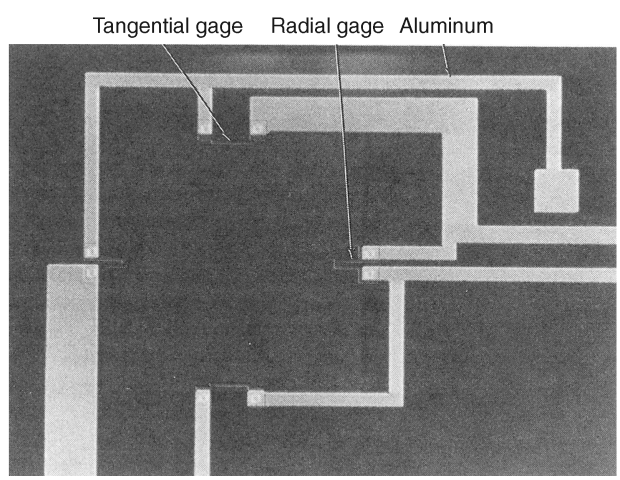

Figure 8. Pressure-sensitive diaphragm of tonometer sensor.

Table 1. Typical Performance of Silicon Tonometer Sensors

	Typical Value[a]		
Parameter	Ref. 26	Ref. 9	Units
Number of elements	8	31	Each
Element spacing	0.75	0.2	mm
Sensitivity	25	25–50	μV/V mmHg
Nonlinearity	3	n.r.	mmHg
Temperature coefficient of sensitivity	−0.25	n.r.	$\%\cdot°C^{-1}$
Temperature coefficient of offset (uncompensated)	1	n.r.	$mmHg\cdot°C^{-1}$
Offset error due to temperature (with temperature compensation)	±1 (estimate)	n.r.	mmHg
Frequency response (flat to <1.0 dB)	>50	n.r.	Hz
Noise	<0.5	n.r.	mmHg

[a]n.r. = not reported.

methods for mounting IC sensors for tonometry in clinical environments.

A clinical tonometer instrument, incorporating many of the features described above, is shown in Fig. 9. Comparable instruments may be obtained from suppliers such as Colin Medical Technology Corp., Komaki, Japan; Hypertension Diagnostics, Inc., Eagan, Minnesota; and AtCor Medical, Sydney, Australia.

MISCELLANEOUS CONSIDERATIONS

One significant advantage of the arterial tonometer is its ability to make noninvasive, nonpainful, continuous measurements for long periods of time. There are several reasons for this superiority over the sphygmomanometer:

1. The sensor is adjusted to partly flatten, but not occlude the radial artery. In contrast, sphygmomanometric systems typically occlude the artery in order to determine systolic pressure.
2. The part of the tonometer sensor representing the arterial riders and side plates of Fig. 3 is ~20 mm in diameter. There may be occlusion of some veins beneath this part of the sensor, but numerous parallel venous paths in the remainder of the wrist allow return venous flow. [The reader may wish to try the following experiment: Place a dime (a U.S. coin ~18 mm in diameter) over your radial artery pulse. Holding your wrist with your free hand, press down on the dime with the thumb to occlude the radial artery. You are now experiencing greater venous occlusion than a tonometer sensor would cause.]
3. There are several venous paths through the wrist. Some of these pass between bones that apparently help protect them from pressure that may be applied externally to the wrist by the mounting strap and other parts of the tonometer sensor.

These factors all help to minimize development of edema distal to a tonometer sensor. Discomfort and development of edema will depend on factors, such as subject-to-subject

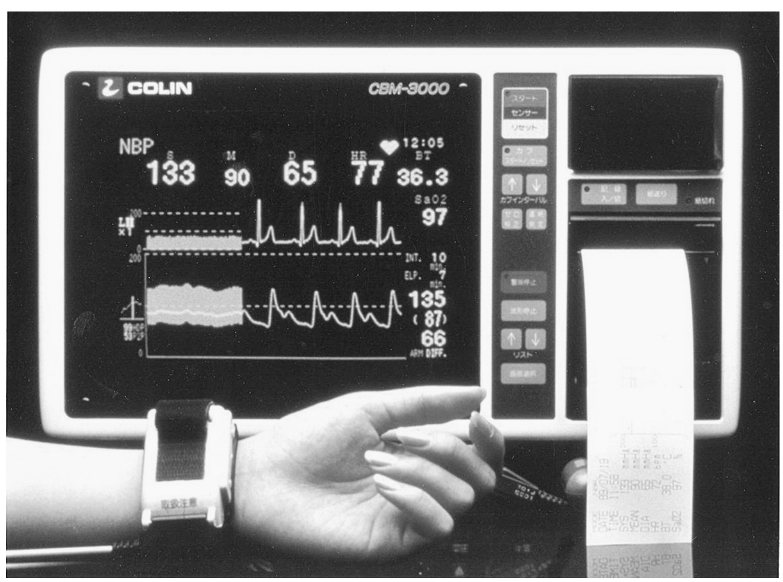

Figure 9. Clinical tonometer instrument.

variations in wrist anatomy, measurement duration, and the hold-down force used. In a study involving 20 conscious, healthy subjects (33) the blood pressure waveform was monitored continuously by tonometry for more than 30 min. The subjects reported no significant discomfort due to the tonometer sensor.

The tonometer's ability to measure blood pressure continuously with minimal distraction to the subject makes it attractive for ambulatory blood pressure monitoring. This application should be feasible in the future, but present instruments do not have sufficient artifact-rejection capability for reliable measurements on ambulatory subjects (21). This is not to say that the arterial tonometer is unusually sensitive to movement artifacts. In a study involving 20 subjects (34), the tonometer was found to be less sensitive to subject movement than photoplethysmographic, quadrapolar impedance plethysmographic, and sphygmomanometric sensors.

Eckerle et al. (35) have taken the first step toward an ambulatory tonometer for blood pressure by developing an ambulatory pulse rate sensor using tonometry. By use of a curved spring, the sensor can be mounted unobtrusively in a watchband <8 mm thick.

Taking an analog signal-processing viewpoint, the blood pressure can be described as the sum of an alternating current (ac) component and a direct current (dc) component. Briefly, the ac component is more easily measured by tonometry than the dc component. More specifically, under clinical conditions, the six conditions listed above may not always be satisfied. When this happens, the tonometer sensor often continues to measure the ac component with good fidelity, while the measurement accuracy of the dc component (on which the familiar systolic and diastolic depend) becomes degraded. Shinoda and others (36–38) have used sphygmomanometric measurements of blood pressure to correct errors in the dc component and thereby produce an output with good waveform fidelity (ac component) and accurate measurement of systolic and diastolic (dc component).

The radial artery is not the only site at which a tonometer may be applied, but most research to date has used this site. Other sites suitable for tonometric measurements include the brachial artery at the inner elbow (the antecubital fossa), the temporal artery in front of the ear, the carotid, and the dorsalis pedis artery on the upper foot.

Anatomical variations of the wrist can make the location and support of the radial artery unsuitable for tonometric pressure measurement. Unsuitability occurs in only a small fraction of the population and such difficult subjects can be recognized by the computer used with multiple-element sensors. In one study involving 6 subjects (7,8) there was one difficult subject, while in another involving 20 subjects (33) there were none.

As described above, a single-element tonometer sensor, such as Fig. 3, can be used for tonometric blood pressure measurement if six conditions are met. The multiple-element tonometer was developed to help simplify tonometric measurements for the clinician (relative to a single-element instrument). Many clinicians (39–45) have reported using multiple-element instruments. Many other clinicians (6,46–54) have used single-element instruments. Chen et al. (44) have used both types. They observe that "Although [the hand-held, single-element tonometer]. . .was probably adequate for brief steady-state data, manual recording was too unstable for accurate pressure tracking during hemodynamic transients, and it introduced an element of user dependence and thus potential bias to the data. The automated [multiple-element tonometer] system circumvented these limitations." We may also observe that the two groups are generally pursuing different applications, suggesting that the choice of optimum sensor type is application dependent.

APPLICATIONS

Perhaps the first clinical application of tonometry was for blood pressure monitoring in surgery and other procedures. Stein and Blick (23) used radial artery tonometry during a catheterization procedure. Kemmotsu et al. (39) used a multiple-element tonometer for surgical monitoring. Several others (40–43,55) have also evaluated the instrument under various surgical and postsurgical situations.

Figure 10 shows a typical blood pressure waveform, obtained with an arterial tonometer from the radial artery of an adult male. Note that systolic and diastolic pressures, as well as pulse rate and dicrotic notch information, can be obtained from the waveform. The subject performed a Valsalva maneuver at the time indicated. The attendant changes in blood pressure and pulse rate are quite clearly indicated. Of course the tonometer measures only the pressure in the underlying artery, not central arterial

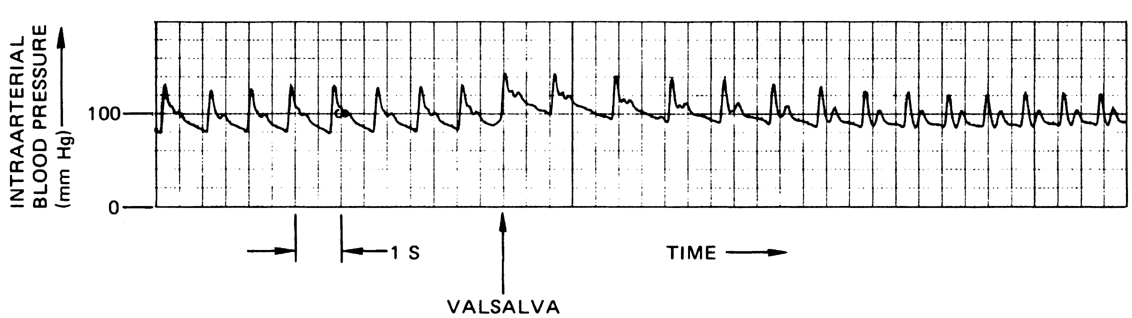

Figure 10. Intraarterial blood pressure waveform.

(aortic) pressure. Central aortic pressure is useful for clinical applications, so there has arisen a desire to calculate central aortic pressure based on a radial pressure obtained with a tonometer.

A brief discussion of circulation dynamics may now help reveal the motivation for some other tonometer applications. Physiologists have long struggled to devise a useful physical model for the circulatory system. Briefly, two complementary models have arisen, a windkessel model and a pulse wave velocity (PWV) model (56,57). In the windkessel model, the circulatory system is represented (often using an electronic analogy) as a small number of lumped elements such as capacitors, inductors, and resistors. In the PWV model, the circulatory system is represented as one or more pipes in which a pulse wave, generated by the heart, travels at a certain velocity. Physiologists and clinicians seek to determine the values of the lumped elements and the magnitude of the PWV by means of noninvasive measurements. Various aspects of the ac component of the pressure waveform of Fig. 10 can be used to estimate the windkessel parameters and PWV.

Focusing on the windkessel model, one can devise a transfer function that relates the pressure at a peripheral site (e.g., the radial) to an input pressure waveform in the aorta (58,44). It is then straightforward (in theory) to compute the inverse of this transfer function. Using this inverse transfer function, one may then calculate the pressure waveform in the aorta based on the peripheral waveform. This technique is potentially very powerful because it allows making a previously invasive measurement (the aortic pressure waveform) by using a noninvasive instrument: a radial artery tonometer.

Several investigators (44,46,58) have evaluated the above technique to determine aortic pressure by mathematical manipulation of a radial artery pressure determined by tonometry. Others (47,59) have evaluated a similar technique to determine aortic pressure from a tonometric carotid pressure measurement.

Numerous investigators (48–51) have used tonometry to estimate windkessel parameters, particularly arterial elasticity. Other investigators (45,52–54) have used it to estimate PWV.

For certain applications, it is sufficient to measure relative, rather than absolute, blood pressure. These include polygraph (lie detector) tests and studies of the physiological effects of various cognitive and physical stressors (e.g., weightlessness and high *-g* aircraft maneuvers). A multiple-element tonometer designed specifically for relative blood pressure measurement has been developed by Eckerle et al. (33) and tested extensively on 20 subjects of both sexes. Subjects were subjected to stressors such as mental arithmetic and cold pressor, and their blood pressures were recorded continuously for periods in excess of 30 min.

MEASUREMENT ACCURACY

Because the accuracy of tonometric blood pressure measurements depends on the size and positioning of the sensor, the value of hold-down force, and the accuracy of the sensor itself, some variability in reported tonometer accuracy can be expected when these factors are not well controlled. In nearly all of the measurements reported prior to 1987 hold-down force was adjusted manually, and in many the tonometer was manually positioned as well. Some improvement in tonometer accuracy and repeatability can be expected from automatic sensor positioning and hold-down force adjustment.

An early validation of the principles of tonometry (60) involved comparison of pressures measured in an exposed canine femoral artery by both a tonometer and an intraarterial catheter. One series of tests involved 15 animals with blood pressure changes being induced by drug injection and vagal stimulation. For this entire series of tests, the difference between pressures measured by the two instruments was never $> 5\%$.

Stein and Blick (23) compared tonometric measurements with direct arterial blood pressures on 20 patients undergoing cardiac catheterization. They found that the tonometer reproduced both the intraarterial waveform and any abrupt changes in pressure caused by various interventions with remarkable fidelity. Specifically, during interventions that increased or decreased systolic pressures by as much as 30%, the tonometric pressure measurement followed the direct arterial pressure within 10% in 92% of the observations.

Weaver et al. (8) compared sphygmomanometric blood pressures with those obtained with a multiple-element tonometer sensor on five subjects of both sexes ranging in weight from 135 to 225 lb (61–102 kg). The standard deviation between the two measurements of systolic and diastolic pressures was 6.5 mmHg (870 Pa), indicating that the tonometer was at least as accurate as the sphygmomanometer.

In 1989, Kemmotsu et al. (39) reported the accuracy of an automated, multiple-element tonometer instrument used for monitoring during surgery. The tonometric measurements showed good correlation ($r = 0.94$, $P < 0.001$ for systolic) with invasive measurements on the contralateral radial artery. Kemmotsu subsequently performed additional studies (40,41) involving surgical monitoring. In the later study (41), involving 60 patients, the mean absolute value of error ranged from 3.6 to 6.6 mmHg (480 to 880 Pa). Standard deviations ranged from 4.5 to 6.2 mmHg (600 to 830 Pa).

Other investigators (42,43,55) have evaluated multiple-element tonometers for surgical and postsurgical monitoring. They found standard deviations ranging from 1.7 (for a single patient) to 14.2 mmHg (230 to 1960 Pa).

Sato et al. (61) evaluated the accuracy of a multiple-element tonometer instrument on conscious subjects subjected to a Valsalva maneuver and a tilting test. This study is of particular interest because they directly addressed the question of frequency response of the tonometer/tissue/artery system. Good frequency response is important for computation of windkessel parameters or PWV as described above. Sato et al. found the frequency response of the tonometer/patient system to be essentially flat from 0 to 5 Hz.

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See also BLOOD PRESSURE MEASUREMENT; IMPEDANCE PLETHYSMOGRAPHY; PERIPHERAL VASCULAR NONINVASIVE MEASUREMENTS.