

*From the School of Optometry,
University of California, Berkeley
Dean: Prof. Kenneth B. Stoddard*

FAST, AUTOMATIC, ELECTRONIC TONOMETERS BASED ON AN EXACT THEORY*)

BY

*R. Stuart Mackay, Ph. D.¹⁾ and Elwin Marg, Ph. D.,
Berkeley, California*

We have been concerned about the need for a fast, automatic, direct-reading tonometer, which is accurate, repeatable and gentle. An instrument with any of these characteristics is desirable but one with them all would be extremely useful. Such an instrument would be of great value not only to the ophthalmologist in his diagnosis and treatment of glaucoma but also to the optometrist who would be able to determine intraocular pressure in his patients without using the topical anesthetics present corneal tonometers demand.

Previous tonometers, mechanical or electronic, measure either the indentation of the cornea produced by a certain size and shape plunger of a given weight, or they measure the force required to flatten a given area of the cornea. We will not discuss these classical instruments, details of which are available in the textbooks (1). Measurement with all classical tonometers requires experience, they are somewhat tedious in their use, and are based upon questionable assumptions. Some of the tonometers to be discussed are subject to some of these same restrictions while others are quite free of them and involve basically different principles.

PRESSURE SENSITIVE ELECTRICAL PAINT

Although a number of transducers of mechanical displacement into electrical signal can be used in the following devices, they will be described in terms of a particular one which led to their development. If a conducting powder is

¹⁾ Radiological Research Laboratory, University of California Medical Center, San Francisco.

*) Received July 14th 1959.

mixed with a binder that retains some flexibility on drying, then one has a paint which, on drying, changes its electrical resistance with pressure.²⁾

Increasing force compresses the material slightly and causes a decrease in resistance to be indicated on a meter attached to electrodes applied to the two surfaces. These electrodes can consist, for example, of the metallic base plate on which the drop of paint is applied and a thin evaporated coating of metal on the upper surface.

If a thin film of paint is pressed against the cornea of the eye (through a thin film of rubber or plastic, say, of the order of 10μ thick to protect both the eye and the transducer), there are three possibilities, each of which conceptually leads to a different tonometer. The area of contact of the eye with the paint can either be *less than*, *equal to*, or *greater than* the area of the paint spot on the base plate. In the *first case*, increasing force applied to the plate will cause a decrease in resistance because of an increase in the area of the paint being pressed upon by the eye. The pressure (force per unit area) is assumed to remain constant. One can construct a tonometer based on this effect by inserting behind the base plate a second force transducer consisting of a constant area of paint which thus transmits to the control circuit a signal indicating the total force applied to the eye. A preset signal from one of the two paint transducers causes the instantaneous signal from the other to be stored in a capacitor »memory device« for later reading. It can be shown that if the reading stored in the capacitor is to be a function of the pressure within the eye, then the characteristics of the paint constituting the front transducer must be nonlinear (i. e., resistance as a function of pressure must not graph as a straight line). If this is not true, then the circuit will be unable to distinguish a low resistance reading on the front transducer due to a high pressure and a small area from a low resistance due to low pressure and large area.

The *second possibility* in which the area of flattening of the eye is just equal to the area of the paint transducer is essentially an electronic equivalent of the Goldmann aplanation tonometer (2). In this form a central paint transducer is surrounded by three small dots of paint. When these small auxiliary transducers are activated momentarily and simultaneously, one has an indication that the eye has been flattened to a circle of just this diameter. The signal from the central transducer at that instant is stored to provide the final indication.

The *third alternative* suggests flattening the eye beyond the area of the paint transducer. Though there were some initial technical difficulties in implementing this method, the advantages shown in Fig. 1 have since made it the

²⁾ Applications of a commercially available form of such material have been given by D. B. Clark, Pressure sensitive material measure explosion forces or footfall of a fly, Product Engineering, 28, 106, (Sept. 16, 1957).

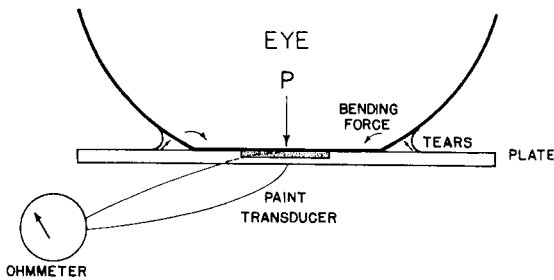


Fig. 1.

The cornea is flattened against a plate in the center of which is a small pressure-indicating device. The main forces exerted on the plate are shown. It is *only* the intraocular pressure (P) that acts on the sensitive surface (paint, pressure transducer) and registers on the ohmmeter, if the sensitive surface is more than covered by the cornea.

preferred one. In this figure we see the cornea of the eye flattened over a distance of approximately 3 mm by the force of the base plate. In the center of this plate is a dried drop of the paint about 2 mm in diameter. In use, the paint is only slightly compressed and so flatness prevails. It will be seen that *the only force applied to the paint transducer is that of the intraocular pressure.*

The reading of the ohmmeter is a unique function of the pressure P existing within the eye. The effects of the rigidity of the cornea and its curvature do not register because the bending of the cornea to flatness is done by a part of the plate beyond the pressure transducer. Thus it is not measured by the instrument. Because the eye is flattened by an insensitive region of the tonometer, there is no added uncertainty if the cornea is astigmatic. The surface tension of tears generates a force pulling the plate to the eye, but in this system there results merely a small increase in external force without any

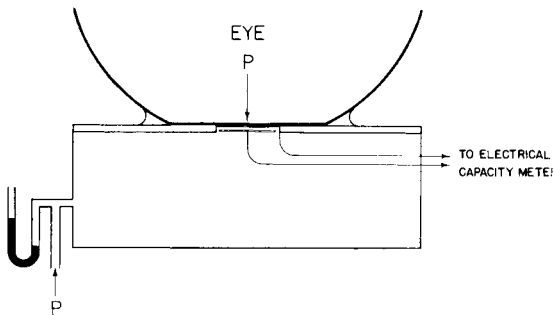


Fig. 2.

The external pressure source, read on the manometer at the left, returns the diaphragm to flatness which is indicated by the capacitance motion detector. The manometric and intraocular pressures are then equal.

change in reading. Tissue tension is a radial force having no component acting on the transducer. Though it might be considered a constant area method, it is not limited by the factors affecting the aplanatic systems. The actual reading appears to be, as expected, relatively independent within limits of the actual total force of the instrument against the eye. It seems clear that the eye must be flattened to beyond the area of the pressure transducer. If it is desired to know the pressure behind a specific structure, then this structure must be flattened. Thus, to flatten the cornea which has a finite thickness and assure flattening of the posterior surface over the area of the transducer, a circle of approximately 3 mm is flattened, following the value given by Goldmann. If the area flattened is too much greater than this then the pressure within the eye will be artificially raised. This matter will be discussed further, later in the article.

ALTERNATIVE FORMS

Although devices based on the properties of these paints are potentially mass producible, and therefore most desirable, we have not yet found an entirely satisfactory paint. We are developing one, but in the meantime the last two forms of tonometer can be constructed around other transducers which at present give greater sensitivity and reproducibility. In each of the following devices, essentially the third scheme will be used in which one registers the force on a fixed area not affected by corneal bending.

A crystal oscillator might be used, the crystal itself being the transducer. It could consist of a 1½ or 2 mm diameter wafer inset flush into the head of the probe.

In Fig. 2 is shown the scheme for a unit in which a metal plate with a small hole covered by a limp conducting diaphragm is pushed against the eye. The electrical capacity between the diaphragm and a back plate is indicated by suitable electronic circuitry. The region behind the diaphragm is sealed so that it is possible to blow air into it. If this unit is pressed against the cornea and the air pressure is raised until the capacity detector indicates that the diaphragm has been returned to the flat condition, then the pressure in the back chamber will be exactly equal to the intraocular pressure. This pressure can then be read, for example, on an associated manometer. The result is almost as if a hollow needle had been inserted into the eye and connected to the manometer. The advantages of this method include: no calibration required, no drift, linearity is automatically assured, and the replacement of any parts has no effect on readings.

The electrical signal from the capacitance detector can activate a magnetic valve or plunger in such a way that the pressure in the back chamber auto-

matically increases until the preset value of capacity is achieved. To the extent that the system responds immediately and if the gain of the electronic system is high, the diaphragm will essentially never be deflected from a perfect plane. The reading can then be obtained as rapidly as the indication of the pressure gauge can be stored. It is desirable that the complete operation of pushing the detector against the eye and having the reading recorded take less than a second so that anesthetics for the cornea need not be employed.

In Fig. 3 is shown a particular version of the previously mentioned feedback scheme. It is not necessary that the signal that is fed back to control the force behind the diaphragm be communicated to the diaphragm by air pressure. Thus, in this figure, we see the motion of a small plunger being sensed by a coil which detects the displacement of a ferrite core. (A circuit related to one independently described elsewhere (3) was developed to sense the motion of a silver vane but, though sensitive, its readings were somewhat unstable and affected by cable motion). The signal indicating a change in position of the piston and vane is detected and amplified to activate the magnet coil shown at the bottom of the plunger. If the plunger tends to move down, the current in this coil is increased and pulls the entire moving portion back to its original position. The magnet current (or voltage) is the useful signal that is recorded. An extraordinary sensitivity of $100 \text{ mV}/\mu$ can be obtained from the detector over a fairly large excursion.

In choosing a detector there are two important factors: first, the transducer's sensitivity to a deflection or displacement, and second, the force required from the test object to produce this displacement in the transducer. If the latter is too high the device may be an excellent displacement indicator but would be useless in this application. In other words, we here need a transducer that requires little energy in the signal to it. The present transducer feeds back

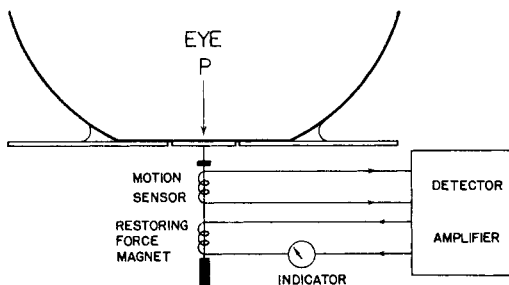


Fig. 3.

In the feedback method the higher the intraocular pressure, the more strongly is the plunger urged forward by the current in the bottom coil (restoring force magnet). Thus the plunger essentially does not move from the plane of the surrounding plate. Pressure is read on the meter whose deflection is proportional to the magnet current.

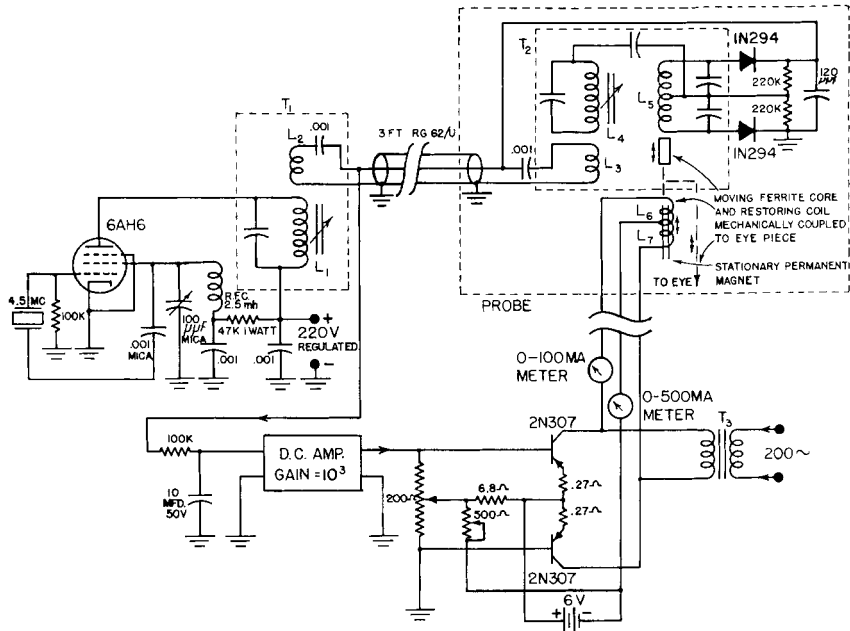


Fig. 4.

Circuit diagram of the tonometer used to obtain the subsequent data. All capacities are in microfarads. T_1 and T_2 are Miller transformers type 1467, the primary of T_1 being L_1 . Coupled to T_1 and T_2 are L_2 and L_3 which are each 16 turns in two layers of number 22 wire. The primary and secondary of T_2 are labeled L_4 and L_5 respectively. The probe must be shielded and the shield must have an axial slit and be connected to the shield of the cable.

such a small force that its nonconstant magnitude does not matter. It is preferable even to a semiconductor strain gauge (4). The feedback system applies a force of about 0.8 g to the eye for a normal intraocular pressure and the deflection of the system is 0.6μ for a pressure of 40 mm Hg. A purely mechanical lever system can be used to monitor these small displacements but they tend to exert forces which are too large. This was the case with a dial-reading displacement measuring device which was tried.

The complete circuit is shown in Fig. 4. With this circuit, sharp bending in the coaxial cable from the probe to the indicator chassis does not change the reading. Lowering the oscillator frequency from 5 or 10 megacycles to 100 kilocycles decreases the sensitivity to uselessness. In the development of this circuit, a pair of opposing detector coils was made to yield double the signal but the results were unsatisfactory; the drift was doubled and the difficulties in tuning and alignment were insupportable. The sensitivity of the circuit is so high that although the mass of the plunger is small, one must guard against an

erroneous reading with automatic recording when rapid movements of the probe are made; this accelerometer effect is caused by the inertia of the plunger. The diameter of the upper surface of the plunger is approximately 1½ mm and the diameter of that part of the eye flattened by the surrounding plate is approximately 3 mm.

In such a feedback system, there is practically no motion if the gain of the over-all system is high. This simplifies the support and friction problem considerably. It was found, however, that friction did somewhat interfere with the ultimate sensitivity of the instrument. Thus, a small, few hundred cycle per second, AC voltage was applied to the bottom magnet coil in the previous configuration. This small steady vibration gives no useful signal but it does continuously result in sliding rather than static friction being the only unwanted force applied to the piston. The resulting unit is effectively frictionless. Optical detection of motion (5) and pneumatic communication of force should provide the ultimate in sensitivity and reduction of friction, if needed. In some of the experiments a commercially available detector of small capacity changes (6) was employed, but the sensitivity was not adequate with it nor with a differential transformer.

Like most feedback circuits, the present one can hunt or oscillate steadily if improperly adjusted, and it is interesting that the frequency is observed to vary with intraocular pressure, as expected. Under these conditions the circuit acts as an electrical negative resistance attached to the coil that is coupled to the eye. This hunting can be stopped by the usual damping procedures used with servomechanisms and regulators.



Fig. 5.

The instrument which is schematically shown in Figs. 3 and 4.

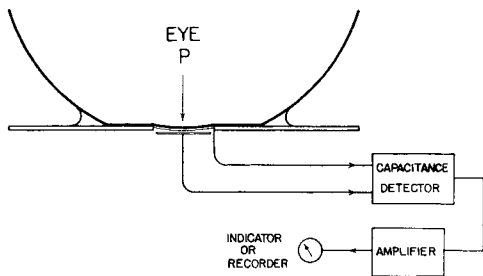


Fig. 6.

The motion of a relatively stiff diaphragm is detected as a measure of pressure with a motion transducer. Without feedback, instability (drift) in the circuits and changes in diaphragm stiffness cause erroneous readings.

In the previous systems; the signal observed is that current required in the bottom coil in order to return the piston to its normal position. However, in any feedback scheme, there will be some tiny residual displacement of the piston or diaphragm. The greater the force, the greater will be this small residual deflection. Thus, one might feel that the entire feedback unit could be replaced by a diaphragm with sufficient rigidity to have the deflection for any force equal to that in the feedback scheme. Hence, with a stiff diaphragm, or a spring-loaded piston, one might have an arrangement as in Fig. 6. The deflection indicated by the capacitance meter would then be a measure of the pressure within the eye since there would be approximate flatness existing. However, any small drift in the amplifier's gain would cause a proportional change in the apparent reading. In the feedback system, a change in gain results in only a small change in the equilibrium position toward which the diaphragm or plunger attempts to return. The reading is thus less affected. The output signal can change either because of a change in gain or a change in pressure. The signal due to the former is small while the signal in the latter is fully amplified in the feedback system. However, the RCA transducer tube 5734 seems quite stable, and because of its stiffness it can be used in forms that do not have feedback.

If the continuous readings of tonography are not required, but only the isolated readings of tonometry, then there is another alternative. The piston or diaphragm can always be started slightly indented from the tonometer surface and then be driven forward for a reading. The force involved at the instant flatness is achieved is the reading to be recorded. The motion can be small and thus the time for a reading short, even though inertial effects and delays must be guarded against. The method can be simpler because no special circuitry need be considered to guard against possible oscillation in the feedback system. In either this or the feedback system there is no case in which the piston should

extend appreciably forward beyond the plate and thus a stop is incorporated to avoid possible trauma to the cornea in the unlikely event of malfunction.

TOTAL FORCE

The theory indicates, and it is observed, that once the eye is flattened sufficiently to cover the paint transducer, the reading is independent of the total force applied within limits. One must keep within bounds limited on the one hand by the necessity to cover the diaphragm or plunger, and on the other by the restriction against mechanically increasing the intraocular pressure.

Rather than requiring any practice or skill in using the instrument, it is desirable that there be some direct indication or control of the limits to be observed. We are attempting to find the final answer to this problems; several approaches are indicated. In the handle of the instrument can be inserted a force transducer (such as a film of the pressure-sensitive paint), which will thus indicate the total force with which the unit is pressed against the eye at any instant. The circuit can be set so that the reading will not be recorded unless the force has at least momentarily reached a value high enough so that any eye would be sufficiently flattened. This approach may prove adequate though in some instances the pressure in the eye may be raised above normal. A ring of pressure-sensitive dots around the main plunger might be electrically connected in series so that only if they are all simultaneously activated, can the reading be recorded. If the reading is recorded electronically just at the instant they are simultaneously activated, then it is likely that the reading will not yet have increased by excess area having been flattened (though if the force then increases to flatten a greater area it does not matter since the reading is already stored). The mechanical analog of this situation would suggest blowing a small annulus of air out in the space between a piston and the surrounding plate. The resistance to flow would go up sharply as the eye would extend beyond the piston and cover this annulus. An interesting way of detecting such an increase in impedance would be to have not a steadily outgoing column of air or liquid, but a vibratory flow of small amplitude. The sudden interruption of this flow by occlusion of the orifice by the eye would interact on the vibrating member within the body of the instrument that was producing this flow. This could be detected by an apparent change in the electrical impedance of the coil producing this motion.

One purely mechanical method of defining the proper position at which a reading is to be taken is as follows. Peripherally on the base plate beyond the sensitive plunger is placed a slightly elevated ring whose surface conforms to the shape of the eyeball. This ring is of such shape and height that when the eye has been pushed up against the base plate enough to flatten just the correct amount of the cornea, the rest of the eye will then come into contact

with the ring. There will then be required a very great increase in force from the hand of the operator in order to push the unit further into the eye. Stated differently, one might say that due to the sudden increase in area, the pressure in the eye will be only slightly increased by even a rather large further increase in total force. Thus, for a fairly wide range in eyeball shapes, one will be led to the correct degree of flattening. Such a method should be possible because there is a finite range of acceptable flattening areas by this method.

As the applied force increases there is a range over which the signal does not change much, i. e. plateaus. This occurs after the plunger is covered but before the intraocular pressure has appreciably changed. By the use of differentiating circuits it may prove possible to detect the instant, and record the signal, that the rate of change of the signal becomes zero but while the rate of change of total force is greater than zero (i. e., the force exerted by the operator is increasing).

Readings can be obtained without automatic devices by simply watching that the flattened area is greater than the plunger but not much greater. It takes several seconds to obtain a reading in this circumstance.

TEST OBSERVATIONS

The readings were obtained by the tonometer shown in Figs. 3, 4 and 5. It was pressed against the cornea until the transducer surface was visibly more than covered and a plateau in the response was evident. Plateaus have been studied using an ink writer rather than a meter, and such records are proving valuable with human subjects.

The result of a test on the intact eye of a urethanized rabbit is given in Fig. 7. If one assumes no change in the intraocular pressure it would be expected that a number of trials would show the same value. A series of ten runs was made, each run using the new tonometer, the Goldmann, the Mueller and the Schiötz, in that order. The readings were taken with all tonometers in regular cyclic fashion and no extended time for »recovery« of the eye was allowed for any of them. Under conditions of this test, only the new tonometer shows good repeatability. The degree of the lack of precision of the other tonometers may be explained at least in part by the inexperience in the technique on the part of the tonometrist. However, the new tonometer measurements were also made without experience. One can only conclude that in these circumstances either the new tonometer is intrinsically superior to the others and/or it requires less experience and technique to obtain precise readings.

Initial calibration of the new tonometer was made with an open manometer connected through a large syringe needle at the equator of the intact eye of the urethanized rabbit. Three readings at each pressure were taken with the

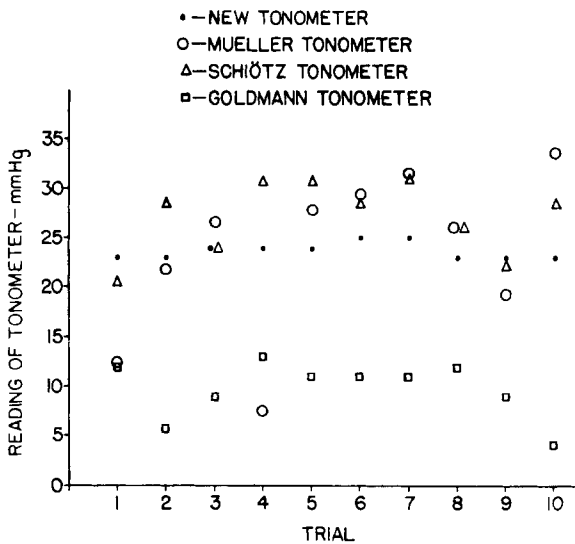


Fig. 7.

Ten trials of four tonometers, the new one, Goldmann, Mueller and Schiötz, were taken on the intact eye of a rabbit with urethan general anesthesia. Each trial consisted of a single measurement with each of the tonometers in the above order. The new tonometer did not use automatic recording.

new tonometer, the Mueller and the Schiötz. Because of difficulties in orientation, only single readings were obtained with the Goldmann after the other data were obtained. Pressure was initially set at 20 mm Hg and raised 5 or 10 mm at a time up to 60 mm Hg. Then the pressure was released back to 20 mm and data obtained in 5 mm steps down to and including 5 mm Hg. Fig. 8 again shows that under the test conditions the new tonometer is far more precise than the older ones. Furthermore, the Mueller and Schiötz cannot read below 5 mm Hg. The new tonometer appears, on the basis of these preliminary data, superior in all respects. However, in fairness to the accuracy of the other tonometers, they were not designed for measurement of the rabbit bulb but for the human eye, whereas the new tonometer is not so restricted. The new tonometer, requiring much less total force against the eye did not induce rotations of the globe which made measurements more difficult with the older indentation instruments. Readings can be taken in any position but the instrument must be set at zero for a given orientation. All observations were made with a rubber condom over the end of the new tonometer.

The presence of a condom makes the endpoint slightly less distinct by effectively reducing the gain of the system. With the present units, the sensitivity is inadequate if one attempts to work through the sclera or closed eye

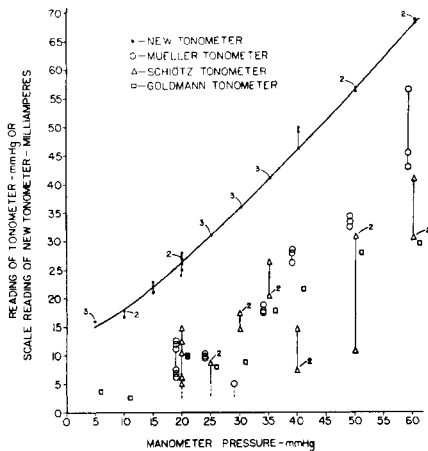


Fig. 8.

Calibration of the tonometers was made on the other eye of the rabbit into which a 16 gauge hypodermic needle was inserted at the equator. A manometer and pressure source were connected to the inserted needle. Three values for each tonometer, except the Goldmann were found for each value of intraocular pressure with an open manometer. The pressure was started at 2 and increased in 5 or 10 mm steps to 60 mm Hg. Then the pressure was returned to 20 mm and reduced in 5 mm steps to 5 mm Hg. Because of the difficulty of orientation with the Goldmann tonometer, only one reading was obtained at most pressures in order of ascending intraocular pressure. The small numbers indicate two or three multiple points as marked. Identical curves were obtained from six eyes of three rabbits with the new tonometer.

lid. It does, however, prove feasible to use these devices in other applications such as the continuous monitoring of blood pressure through intact vessels.

The present device could be used for tonography if it is held in contact against the eye with a fixed, higher than normal force. Supplementary experiments would have to be performed in order to ascertain the volume of the aqueous expressed for any given reading. As with any tonometer one here infers two pieces of information from a single observation.

An improved form of tonography could be achieved by maintaining a fixed area of contact through the previously mentioned detecting trio of dots of transducer paint. Methods of applying a variable force to maintain a fixed area are well known in the electronic art but it is not appropriate to discuss such actuators here.

An »N« shaped response rather than a single plateau has been observed. This may be concerned with corneal buckling, a phenomenon which will require further investigation.

No topical anesthesia was required in 6 of 7 human subjects. One subject could not be measured without a corneal anesthetic because of an uncontrollable blepharospasm upon corneal contact.

It should be noted that all of the circuits that have been described in connection with these devices are simple and well known, and thus relatively inexpensive. No auxiliary devices, such as expensive slit lamps and corneal microscopes, need be employed with them. Complicated calibrations are not required periodically. Calibration may be readily accomplished in the piston instrument by tilting the probe at various given angles from horizontal to vertical. As the piston of known mass becomes more vertically oriented, its increased gravitational force on the measuring transducer can act as a calibration standard. The signal for flatness in the instrument is easily checked by pushing the probe against any flat object such as a sheet of glass. Thus, such equipment is within the means, skill and limitations of most refractionists. Furthermore, it is hoped that these instruments in their definitive forms may prove of value not only in the hands of optometrists and ophthalmologists but also, since they do not require much skill, may be used generally as screening devices for detecting early, simple glaucoma.

The help of Mr. Raymond Oechsli in the development and construction of the circuits and equipment is gratefully acknowledged.

SUMMARY

Several fast, automatic, electronic tonometers have been discussed, some with an exact theory. The latter are not significantly affected by corneal elasticity or rigidity, corneal curvature or astigmatism, or surface tension of lacrimal fluid. Preliminary data make them appear more accurate, repeatable and gentle than previous tonometers. They can be used very quickly and therefore in many individuals without corneal anesthesia, are easier to use, more convenient to read and can be applied in any position. The surface applied to the cornea is essentially flat and covered with a sterilizable and disposable film of rubber.

REFERENCES

1. *Duke-Elder, W. S.*: Textbook of Ophthalmology, Vol. I, 2nd Impression, p. 406, 1938.
2. *Moses, Robert A.*: The Goldmann aplanation tonometer, *American Journal of Ophthalmology*, 46/6, 865-869, 1958.
3. *Machin, E. K.*: Two capacitance transducer circuits, *J. Sci. Inst.* 35, 434, Fig. 2, Nov. 1958.
4. *Mason, W. P.*: Semiconductors in strain gauges, *Bell Labs Record*, 37, 7, January 1959.
5. *Goley, M. J. E.*: Theory of pneumatic infra-red detector, *Rev. Sci. Inst.* 18, 855, 1947; 18, 359, 1947.
6. *Lion, K. S.*: Mechanic-electric transducer, *Rev. Sci. Inst.*, 27, 222, 1956.